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TECHNOLOGY ASSESSMENT OF ADVANCED PROPULSION SYSTEMS FOR SOME CLASSES OF COMBAT VEHICLES

Volume I. Summary and Main Text

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This paper presents the results of a study of propulsion systems for surface combat vehicles which is intended to provide information useful to the Defense Advanced Research Projects Agency in identifying high-payoff R&D prospects. The primary purposes of the paper are to: (1) quantify the technological advances needed to make major improvements in appropriate military propulsion systems and indicate relative payoffs; and (2) provide criteria for evaluation of new propulsion system or

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19. vehicle wheels; propellers (marine); hydraulic jets

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subsystem concepts. The scope of the study is limited to an assessment of propulsion systems for four classes of surface combat vehicles: (1) main battle tanks; (2) light, tracked land combat vehicles; (3) high-mobility land combat vehicles; and (4) high-speed (more than 50 knots) ships. For propulsion subsystems, five engine types (Otto, Diesel, gas turbine, closed Brayton, Stirling), three transmission types (mechanical, hydrodynamic, electrical), and four thruster types (tracks, wheels, propellers, waterjets) are examined in some detail.

Results are presented in terms of technology goals which are within the bounds of what is judged to be physically possible and which together in relevant sets would have a major impact on the cost or performance of armored land combat vehicles or of high-speed ships. Relative payoffs within each set of goals are also estimated.

This report is in three volumes.

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- E. William Beans, University of Toledo--Otto-cycle engines (Appendix C)
- M.G. Bekker, consultant--thrusters for ground combat vehicles (Appendix J)
- Peter C. Bertelson, consultant--mechanical and hydromechanical transmissions (Appendix H)
- A. Douglas Carmichael, MIT--closed Brayton-cycle engines (Appendix F) and thrusters for high-speed oceangoing ships (Appendix K)
- P.C.T. de Boer, Cornell University--Diesel engines (Appendix D)
- B.L. Fletcher, consultant--land combat vehicles (Appendix A)
- James E.A. John, University of Ohio--Otto-cycle engines (Appendix C)
- James L. Kirtley, MIT--electrical transmissions (Appendix I)
- Philip Mandel, MIT--high-speed ships (Appendix B)

- Joseph L. Smith, Jr., MIT--electrical transmissions (Appendix I)
- Graham Walker, University of Calgary--Stirling engines (Appendix G)
- David Gordon Wilson, MIT--open Brayton-cycle engines (Appendix E)

In addition to the specific contributions just cited, these individuals also provided greatly appreciated counsel to the authors throughout the study.

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ABSTRACT

This paper presents the results of a study of propulsion systems for surface combat vehicles which is intended to provide information useful to the Defense Advanced Research Projects Agency in identifying high-payoff R&D prospects. The primary purposes of the paper are to: (1) quantify the technological advances needed to make major improvements in appropriate military propulsion systems and indicate relative payoffs; and (2) provide criteria for evaluation of new propulsion system or subsystem concepts. The scope of the study is limited to an assessment of propulsion systems for four classes of surface combat vehicles: (1) main battle tanks; (2) light, tracked land combat vehicles; (3) high-mobility land combat vehicles; and (4) high-speed (more than 50 knots) ships. For propulsion subsystems, five engine types (Otto, Diesel, gas turbine, closed Brayton, Stirling), three transmission types (mechanical, hydrodynamic, electrical), and four thruster types (tracks, wheels, propellers, waterjets) are examined in some detail.

Results are presented in terms of technology goals which are within the bounds of what is judged to be physically possible and which together in relevant sets would have a major impact on the cost or performance of armored land combat vehicles or of high-speed ships. Relative payoffs within each set of goals are also estimated.

CONTENTS

GLOSSARY

ADV	Advanced
AGT 1500	Gas turbine tank engine, ~1500 shp (Lycoming)
APC	Armored personnel carrier
B	Breadth
c	Specific heat
c_p	Constant pressure
CP	constant pressure
DARPA	Defense Advanced Research Projects Agency
E_{cr}	Cruise endurance
F	Precompression power/total compression power
GVW	Gross vehicle weight
HMPT-500	Hydromechanical transmission for tracked vehicles (General Electric)
$(HP\text{-}HRs)_{cr}$	Total energy used to get maximum range
HSS	High-speed ship
K_o	Fraction of vehicle weight in propulsion system together with its fuel supply
L	Length
LCV	Land combat vehicle
LM 2500	Marine gas turbine, ~23000 shp (General Electric)
lp	Limited pressure
$\dot{m}$	Mass flow rate

MBT	Main battle tank
$\dot{m}_f$	Mass flow rate directly into working fluid
MICV	Mechanized infantry combat vehicle
N	Rotational speed
N_{cyl}	Number of cylinders
P_{add}	Power addition
P_{cr}	Cruise thrust power
P_i	Inlet power
P_{int}	Internal power
P_{it}	Total internal power transfer = $P_{int} + P_x$
P_{loss}	Loss in power output
P_{max}	Maximum thrust power
P_o	Power output; delivered shaft horsepower of engine
P_x	Intermediate power transfer
P1	High relative payoff
P2	Relative payoff not as high as P1
Q_i	Propulsion system parameter
r	Compression ratio
r_{cv}	Pressure ratio at constant volume
R&D	Research and development
SC_i	Cost sensitivity factor
SEGMAG	Segmented-magnet motors and generators (Westinghouse)
SES	Surface-effect ship
SFC	Specific fuel consumption, propulsion system
sfc_e	Specific fuel consumption, engine

sv_e	Specific volume, engine
SV_{ps}	Specific volume, propulsion system
SV_{psp}	Specific volume, propulsion system within armored volume
sv_x	Specific volume, transmission
SW	Specific weight
sw_e	Specific weight, engine
SW_{ps}	Specific weight, propulsion system
SW_{psp}	Specific weight, propulsion system within armored volume
SW_{psw}	Specific weight, propulsion system exterior to armored volume
sw_x	Specific weight, transmission
sw_{xt}	Specific weight, transmission and thruster together
T_1	Minimum working temperature
T_2	Working temperature before combustion begins
V_{cr}	Speed for maximum endurance
V_D	Piston displacement
V_{max}	Maximum speed
W	Engine weight
W_c	Configuration weight (structure plus armor)
W_F	Fuel weight
W_L	Payload weight
W_{ps}	Propulsion system weight
W_{psp}	Weight of propulsion system within armored volume
W_{psw}	Weight of propulsion system exterior to armored volume
W_t	Weight of thruster

W_v	Gross vehicle weight
α	Ratio of structural weight in hull to weight of systems carried in hull
β	Ratio of armor weight in hull to volume of systems carried in hull
γ	Ratio of specific heats of a gas
ΔH	Heat of combustion
η_t	Efficiency of thruster
η_x	Efficiency of transmission
η_{xt}	Efficiency of thruster and transmission together
ρ_F	Fuel density
ρ_i	Density of i^{th} element = W_i/∇_i
ρ_L	Density of payload
ρ_{psp}	Density of propulsion system within armored volume
∇_F	Fuel volume
∇_L	Payload volume
∇_{ps}	Propulsion system volume
∇_{psp}	Volume of propulsion system within armored volume
∇_{psw}	Volume of propulsion system exterior to armored volume
$\$_F$	Fuel cost
$\$_{mp}$	Maintenance cost, propulsion system
$\$_{mv}$	Maintenance cost, vehicle platform without propulsion system costs
$\$_{pp}$	Procurement cost, propulsion system
$\$_{pv}$	Procurement cost, vehicle platform without propulsion system costs
$\$_T$	Vehicle platform cost, life cycle

SUMMARY

A. PURPOSE AND SCOPE

This paper presents the results of a study of propulsion systems for land and sea combat vehicles that is intended to provide information useful to the Defense Advanced Research Projects Agency (DARPA) in identifying high-payoff R&D prospects.

The genesis of the study was in questions that arose at a DARPA-sponsored panel discussion of R&D programs for advanced military propulsion systems. The general nature of the questions concerned the relationship between an advance in technology and its resultant impact when used in a military propulsion system. A number of such questions seemed to be accessible to quantitative analysis, the results of which could provide useful guidance to R&D planning and useful criteria for evaluating unsolicited proposals. Hence, this study was proposed. Its primary purposes are:

- To quantify the technological advances needed to make major improvements in selected propulsion systems and to show relative payoffs
- To provide criteria for the evaluation of new propulsion system or subsystem concepts.

A propulsion system is defined here to include three major subsystems: an engine, a transmission, and a thruster. The scope of the study is limited to an assessment of propulsion systems for four classes of surface combat vehicles: (1) main battle tanks; (2) light, tracked land combat vehicles; (3) high-mobility land combat vehicles; and (4) high-speed (>50-knot) ships. For propulsion subsystems, five engine types

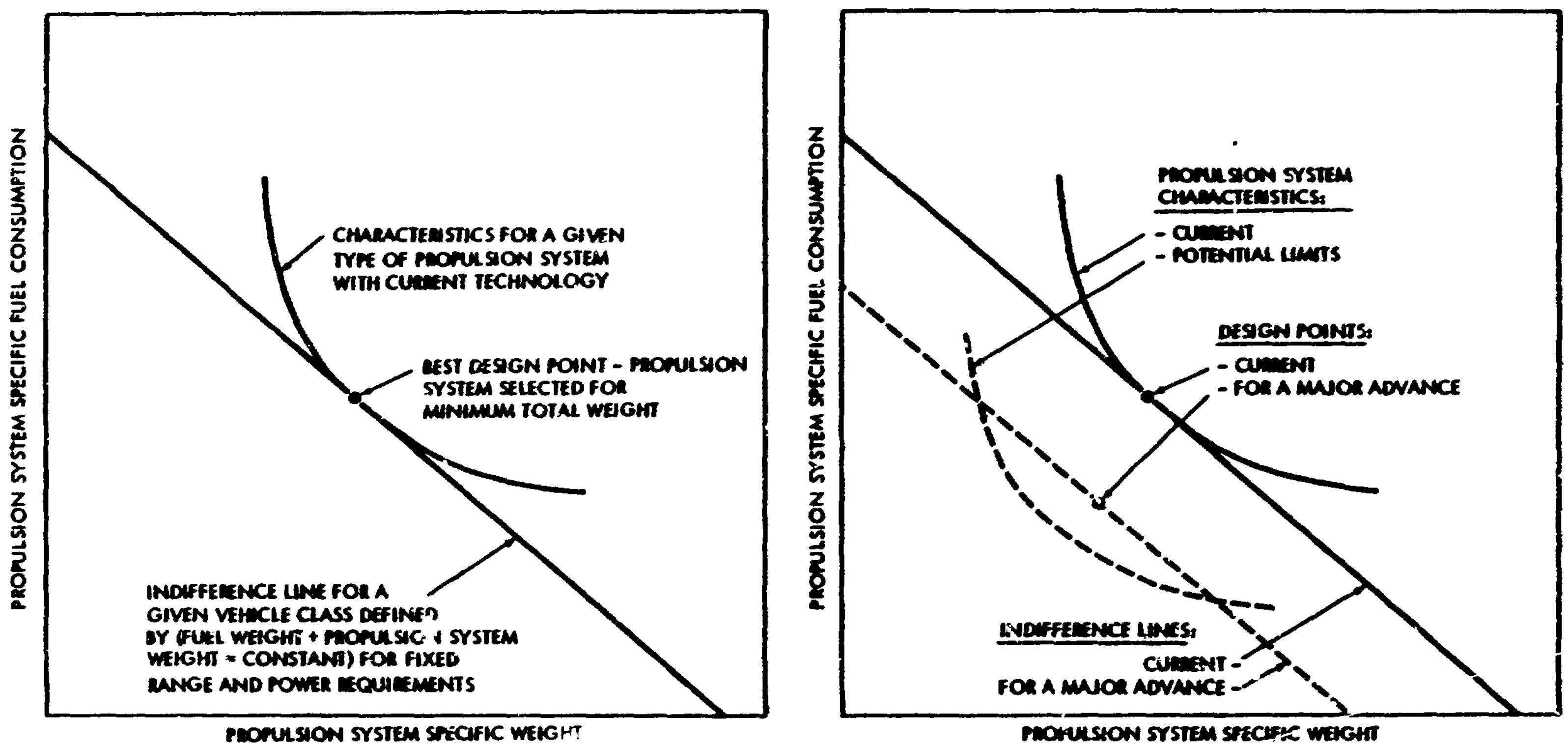
(Otto, Diesel, gas turbine, closed Brayton, Stirling), three transmission types (mechanical, hydrodynamic/hydromechanical, electrical), and four thruster types (tracks, wheels, propellers, waterjets) are examined in some detail. Hydrocarbon fuels are assumed throughout the study.

B. APPROACH

1. Conceptual Basis

The basis of the analysis is to compare the size and efficiency characteristics of given propulsion systems (i.e., engine-transmission-thruster combinations) with the characteristics needed to meet the weight and volume constraints imposed by the vehicle characteristics. The concept can be illustrated by considering a vehicle whose primary design constraint is minimum weight; then the comparison can be made in terms of the propulsion system parameters, specific fuel consumption, and specific weight (weight per unit power), as shown in Fig. S-1a. In this figure the vehicle indifference line represents the tradeoff between fuel and propulsion system that keeps the sum of their weights constant for given power and range requirements, and hence it defines parameter values that give no first-order impact on the vehicle. The propulsion system characteristics line in Fig. S-1a represents the tradeoff between weight and efficiency that is always possible in power conversion devices at a given state of technology. The tangent point of the two lines is the best design point, i.e., the point where the propulsion system characteristics available match those needed, at minimum vehicle weight.

What is done in this analysis is to look for a new design point by defining how far the vehicle indifference line must be shifted to have a major impact on the vehicle, and how far the propulsion system characteristics curve may be shifted before reaching its potential physical or practical limits. If a new



a. Matching current propulsion system and vehicle characteristics.

b. Projecting characteristics required for a major advance.

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FIGURE S-1. Conceptual basis for establishing propulsion system characteristics needed to make a major advance in a specific vehicle application.

design point can be found, as shown conceptually in Fig. S-1b, this establishes "major advance" goals for a given propulsion system in a given vehicle class. This procedure is used to decide which specific propulsion systems have the potential for contributing a major advance and to set goals for those that do. The system goals are then used to establish a set of subsystem goals and a related set of technology advances.

2. Measures and Criteria for Quantitative Estimates

To quantify the above concepts requires selecting suitable measures and setting appropriate criteria, which are summarized here (see Section I-C for more detail). Several of the criteria are arbitrary, but the effect of changing them on the quantitative results can generally be easily assessed.

a. Propulsion System Performance Characteristics. Specific weight, specific volume, and specific fuel consumption are considered the basic performance characteristics of propulsion systems. These characteristics were chosen as basic because only if a proposed system passes the primary tests of size and efficiency do other characteristics such as noise and exhaust signature become important. Specific weight and volume are referenced to the maximum power condition, because this combination determines the overall weight of the propulsion system and how much space it occupies. Specific fuel consumption is referenced to 25% power, because the duty cycles of the vehicles considered in this study characteristically involve low-power operation most of the time.

As indicated in Fig. S-1b, potential physical or practical limits to the performance of propulsion systems are estimated. This is accomplished for each subsystem by an examination of the energy conversion processes it performs and the components it uses to carry out such processes (see appendices in Vols. II and III). Potential limits on these processes and components are evaluated and form the basis for estimates of the subsystem

performance limits and of the technology impacts on this performance. The criterion in selecting limits is that they are judged to be within the bounds of what is physically possible. No judgment of the R&D necessary to reach them is made.

b. Impact Measures. A measure is needed to evaluate the impact of a change in propulsion system characteristics on the vehicle. This presents a difficulty in that an improved propulsion system can be used to design a variety of vehicles with different performance, size, and/or cost characteristics. The measure used here is the potential reduction in cost per unit payload of a selected reference vehicle with fixed performance characteristics, where cost includes the procurement and the direct operating and maintenance costs over an appropriate life for the entire vehicle, exclusive of its combat payload costs.*

An advantage of this measure is that it allows estimation of the impact of changes in propulsion system cost together with technology changes. In addition, changes in this measure, at constant vehicle performance, can be viewed as a crude indicator of changes in vehicle cost-effectiveness.

c. Vehicle Indifference Lines--Payoffs from Technology Advances. To calculate vehicle weight indifference lines, characteristic weight and volume distributions between armament, structure, fuel and propulsion system, as well as propulsion power and range requirements are established for each vehicle (Appendices A and B). The criterion is that such characteristics be consistent with service-proven designs. Vehicle weight indifference lines are then determined by relating fuel weight and volume requirements to specific fuel consumption and by relating propulsion system weight and volume requirements to the specific weight of the propulsion system.

To calculate cost impact, characteristic cost distributions among the vehicle platform elements (structure, fuel,

*This definition is implied wherever the term "cost" is used.

propulsion system) are estimated in this study for each reference design (Section II and Appendix A). Then, using the combined cost and performance characteristics selected for each vehicle class, the cost impact of given changes in the propulsion system is calculated. In this calculation, it is assumed that the cost per unit weight of structural element and of fuel is constant; and the cost per unit power of the propulsion system stays constant, which seems to agree with historical data.

It should be noted that when cost impacts are evaluated in this way, keeping vehicle performance constant, a vehicle weight indifference line is a close approximation to a cost indifference line.

These models are rather crude but are judged to be adequate for the purpose of making payoff estimates. The relative payoff of each of the technology advances needed to reach a new design point (e.g., Fig. S-1b) is evaluated in terms of its relative contribution to the total reduction in cost per unit payload at the new design point.

d. Criteria for a Major Advance. In terms of the concepts given above, a major advance is determined by a given shift in the vehicle indifference line. To establish goals for the power train in the three classes of land combat vehicles, the criterion of a 20-25% reduction in cost per unit payload is used to define the new indifference line. For the high-speed ship class, the criterion used is the reduction of propulsion system weight fraction from 0.5 to 0.35, the latter value being consistent with service-proven designs of naval escorts. These criteria are arbitrary, of course, but are judged to be consistent with the DARPA charter of looking for high-payoff R&D projects.

3. Method of Presenting Results

By using the above approach, the results of the study can be presented in terms of *suitable goals* for propulsion system and subsystem characteristics and in terms of the related

technologies needed to reach these goals. In relating system goals to equivalent goals for subsystems, the set of subsystem goals is selected to be of approximately equal difficulty to achieve. The criterion used is that the goals for all relevant parameters represent equal fractional improvements between the current state-of-the-art values and the estimated limits.

In summary, then, suitable goals have these properties:

- They are applicable only to a specified class of vehicle and type of propulsion system
- If achieved in concert, they would have a major impact on the relevant vehicle class
- They do not exceed the estimated limits of physical and practical possibility
- They are estimated to be of approximately equal difficulty to achieve.

As noted above, it is assumed that the goal of keeping propulsion system cost per unit power constant is attained. However, the impacts of changes in this cost parameter are estimated.

4. General Comments; Limitations of the Analysis

The goals presented here are only intended to provide guidance in evaluating high-risk exploratory developments. Additional considerations would be involved in pursuing such efforts into advanced or engineering developments.

The analysis of course cannot avoid several obvious difficulties: other classes of vehicles or other desired impacts will produce different goals; propulsion system characteristics other than those considered here and possibly not yet discovered could render the present system and subsystem goals obsolete; and the limits of subsystem performance and their relative difficulty of achievement are uncertain and subject to judgmental considerations. All of these difficulties and uncertainties do

not, in our opinion, detract substantially from the validity of the present results for evaluating high-risk exploratory developments; they do serve, however, as cautions to interpretation of the results.

This analysis attempts to avoid three pitfalls frequently encountered in determining the impact of advanced technology on vehicle performance: (1) the use of unrealistic reference vehicles (i.e., vehicles with cost per unit payload far in excess of past proven designs); (2) failure to consider the interaction of a subsystem with the other interacting subsystems; and (3) failure to consider how advanced technology may impact on competing subsystems.

Details of the technologies that determine the performance characteristics of the subsystems studied are covered in a series of appendices in Volumes II and III. Apart from their relevance to the analysis in this volume, the appendices should be of particular interest to specialists in the respective technologies.

C. RESULTS

1. General Conclusions

A basic conclusion of this study is that there are potentially achievable technology advances that would have a major impact on the cost or performance of armored land combat vehicles and of high-speed ships. Such advances do, however, represent large departures from the current state of the art. Hence, programs for their attainment can be expected to involve high-risk R&D approaches.

Among the propulsion subsystems, engines contribute most to the total impact, their greatest improvements arising from potential increases in ideal efficiency by going to higher temperature and pressure. This puts R&D emphasis heavily on improved material properties. On the other hand, with respect

to the prospects for innovative engines, the evidence is that thermodynamic cycles or compression and expansion mechanisms different from those examined here offer less potential return, largely because the developed engine types cover the map of potential size and efficiency improvements quite completely. That is, in these terms, there seem to be no "windows" in which an innovative engine would not be in direct competition with an improved developed engine.

The contribution of the advanced-technology transmissions studied is less than that of engines, largely because the scope for size reduction and efficiency improvements is more limited. The results for land combat vehicles indicate that future technological improvements could leave transmissions considerably bigger than the engines--an apparent anomaly. Unlike engines, transmissions have two avenues of innovation that may be promising: one is to combine engine and transmission functions and deliver shaft power at the point of use; the other is to use electrical transmissions with innovative conversion machinery. Such innovative electric transmissions may also show payoffs in high-speed ships. Neither of these avenues was evaluated in this study.

For the thrusters studied, as for transmissions, the scope for improvements is more limited than for engines. For land combat vehicles, the most promising avenue is to reduce the weight of tracks. Here again, R&D emphasis is on improved materials. For waterjet thrusters on high-speed ships, the payoff is in improved efficiency without significant weight changes, which puts the R&D emphasis on design improvements.

2. Quantitative System Results for Specific Applications

In terms of the propulsion system parameters specific fuel consumption and specific weight, the quantitative results are shown for main battle tanks in Fig. S-2 and for high-speed ships in Fig. S-3 (see Sections II-E and II-F). To have a

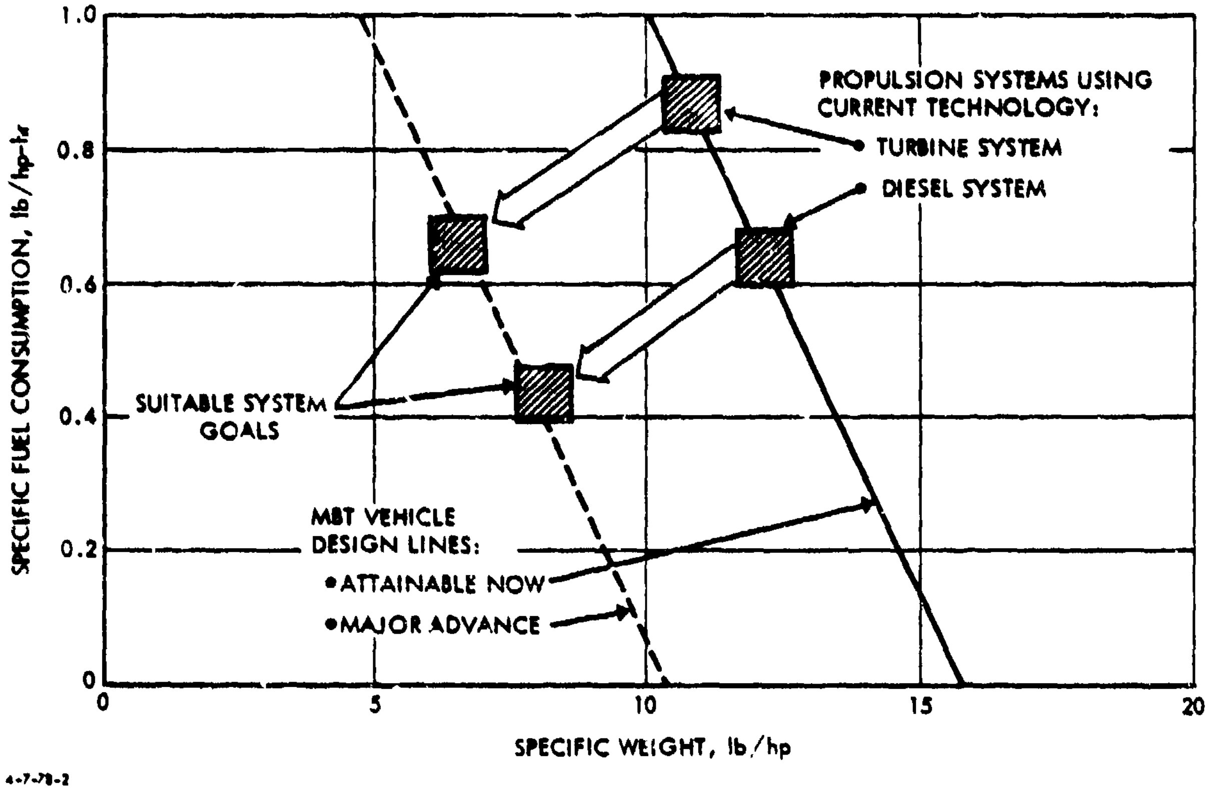

FIGURE S-2. Suitable propulsion system goals for MBTs. Reference hp is delivered thrust power. Propulsion system weights include a hydrodynamic transmission and final drive but do not include suspension and tracks.

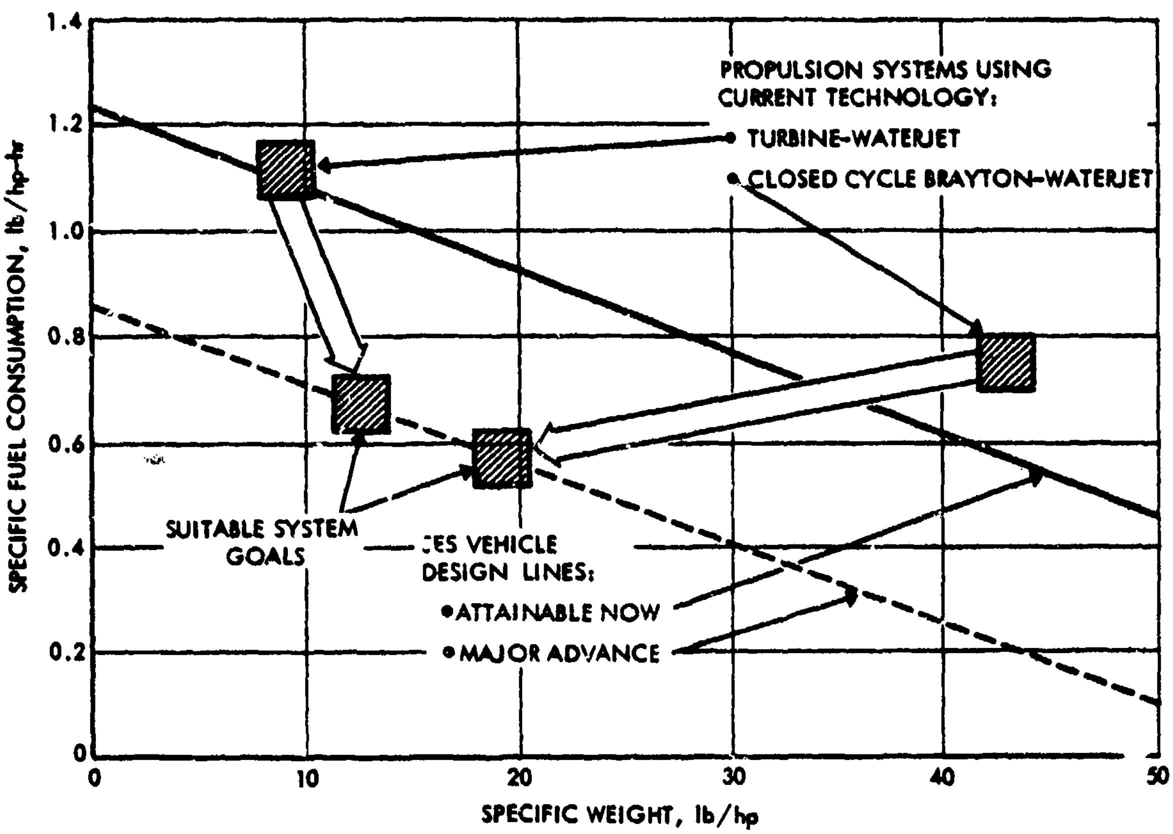

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FIGURE S-3. Suitable propulsion system goals for high-speed oceangoing ships. SES = surface effect ship. Reference hp is delivered thrust power. The propulsion system weights include a reduction gear but no shafting.

major impact, the system parameters* must be improved so as to lie on or below the vehicle design line marked "major advance." In each case, two of the systems studied were found to have potential limits able to meet the major advance requirement for that vehicle class, and suitable goals for each system are shown in the figures. For tanks, specific volume is also an important parameter, and Fig. S-2 is based on the assumption that specific volume is proportional to specific weight (i.e., density remains constant).

Figures S-2 and S-3 address a part of the stated objectives in that they provide (1) the amount of improvements in known systems needed to produce a major impact, and (2) criteria for evaluating new, unspecified system concepts. Major practical interest, however, is in what this means in terms of subsystem (i.e., engine, transmission, thruster) improvements, what technology advances are involved in such improvements, and what is the relative contribution of the various improvements to meeting the overall goals. Such information was developed in the study and is summarized next.

3. Associated Subsystem and Technology Results

a. Armored Land Combat Vehicles (LCVs). It was found that in terms of propulsion system goals, the results for main battle tanks (MBTs), light tracked LCVs, and high-mobility LCVs were essentially the same.** Differences occurred only in the relative payoffs, and these were mainly a reduction in the payoffs associated with specific volume changes in the smaller vehicles, due to their lighter armor. Hence, we can take the results for

*These system parameters are referenced to installed weights and delivered thrust power. The numerical values are therefore higher than if they were referenced to uninstalled weights and shaft horsepower.

**Though the power level required for tanks is about 1200-1500 hp, while for the other two classes of LCVs it is about 250-500 hp.

main battle tanks as characteristic of a broader class of armored land combat vehicles, remembering that volume reductions lose significance in light LCVs.

(1) Diesel System for MBTs. The breakdown of suitable system goals into subsystem goals is given in the following table (Section III-D-1). Also, the relative contribution of reaching each subsystem goal is indicated under Relative Payoff. In this table, sfc is specific fuel consumption, sw is specific weight, sv is specific volume, and η is efficiency. Subscript e stands for engine, subscript x for transmission, and subscript t for thruster.

Subsystem Type	Subsystem Parameter[a]	Units	Current Value	Suitable Goals	Relative Payoff (Σ = 1)
Diesel Engine	sfc_e	lb/hp-hr	0.44	0.32	0.17
	sw_e	lb/hp	4.3	1.5	0.35
	sv_e	ft^3/hp	0.095	0.042	0.26
Hydrodynamic Transmission	η_x	--	0.76	0.782	0.09
	sw_x	lb/hp	6.6	4.7	0.09
	sv_x	ft^3/hp	0.055	0.039	0.04
Track[b]	η_t	--	0.91[c]	0.91	--

[a]The reference power is the output power of each subsystem. Transmission cooling power is included in computing η_x.

[b]The thruster for land vehicles includes both tracks and suspension. Its weight is insensitive to the power it transmits but instead is determined by the supporting loads it carries. Hence, specific weight (i.e., weight per unit power) is not an appropriate parameter and thruster weight is considered independently of other propulsion system characteristics (see Section II).

[c]Nominal value under average load conditions.

Two major observations can be made. First, the greatest relative payoffs are associated with engine improvements, which is a direct consequence of our estimate that improvements within the limits of possibility are greater for engines than for

transmissions,* combined with the relative importance of the engine in the propulsion system. Second, with respect to the engine, the higher payoffs are associated with weight and size reduction, rather than with reduction of sfc.

The related technology goals and their relative payoffs are given below. As might be expected, the relative payoffs associated with goals in this form are more difficult to quantify and hence are indicated here in a simple form: high relative payoff (P1) and not-so-high relative payoff (P2).

For diesel engines (Section IV-A-3):

- Improved ideal cycle performance to a level of 73% thermal efficiency and correspondingly high specific power; a compound engine, peak cylinder pressures in excess of 3000 psi, and peak equivalence ratios of 0.9 are indicated (P1).
- Reduction of heat transfer losses by two-thirds and associated reduction in cooling system weight by two-thirds; quasi-adiabatic operation is indicated (P2).
- Increase in the volume flow per unit displacement by one-third; higher piston speeds are indicated (P2).
- Reduction of the weight per unit displacement of displacement-related components by a factor of 4; lightweight materials are indicated (P1).

For hydrodynamic transmissions (Section IV-B-3):

- Reduction in weight of mechanical components by 30% through use of improved materials (P2).
- Reduction in losses in fluid-mechanical energy conversions by 25% while maintaining weight through improved design (P2).

*We assume automatic transmissions will continue to be specified even though a vehicle penalty, compared to purely mechanical transmissions, is involved in their use.

(2) Gas Turbine Systems for MBTs. Subsystem goals and relative payoffs are shown in the following table (Section III-D-1).

Subsystem Type	Subsystem Parameter	Units	Current Value	Suitable Goals	Relative Payoff (Σ = 1)
Turbine Engine	sfc_e	lb/hp-hr	0.60	0.47	0.17
	sw_e	lb/hp	2.6	0.78	0.26
	sv_e	ft^3/hp	0.053	0.016	0.26
Hydrodynamic Transmission	η_x	--	0.76	0.784	0.09
	sw_x	lb/hp	6.6	4.75	0.18
	sv_x	ft^3/hp	0.055	0.039	0.04
Track	η_t	--	0.91	0.91	--

The same two observations as for the corresponding diesel system apply here also: the bulk of the payoff is associated with engine improvements, and the higher payoffs of engine improvements are associated with weight and size reductions. It is to be noted that, relative to diesel systems, engine improvements are of slightly lesser importance, which is to be expected because of the relatively smaller size and weight of gas turbine engines.

The technology goals associated with these improvements in gas turbine engines are (Section IV-A-4):

- Improved ideal cycle performance to a level of 64% thermal efficiency and correspondingly high specific power; a modestly regenerated engine operating at maximum temperatures of about 2500°F is indicated (P1).
- Maintenance of component loss levels at current best values (P2).
- Maintenance of component specific weights (weight per unit energy transfer rate of the component) at current levels; of particular importance is the heat exchanger (P1).

In addition, any fundamental improvements in part-power performance or in reduction of size and weight of heat exchangers could be used to alleviate the maximum temperature required.

For hydrodynamic transmissions, the technology goals are essentially the same as for diesel systems. However, the payoffs associated with size reduction are larger in this case because of the relatively larger size of the transmission.*

(3) Tracks. As noted above, tracks are taken to include the suspension and are treated separately. The basic reason is that, though tracks are part of the propulsion system, their weight is dependent on the gross weight of the vehicle and not on the power they transmit (see Appendix K for detail). Hence, specific power is not a useful parameter for evaluating tracks as it is for engines and transmissions. Tracks (including suspensions) were found to constitute about 22% of the gross weight of an armored vehicle. A reduction in track weight of 30% through design changes and improved materials is a suitable goal. The relative payoff of reaching that goal is significant--about one-half the payoff of reaching the combined engine and transmission goals (Section III-D-1).

(4) Propulsion System Cost Considerations. The suitable goals presented above, if achieved in concert, will produce a 20-25% reduction in cost per unit payload, assuming that the goal of maintaining cost per unit power in the propulsion system is also attained. Without further information, this is a reasonable assumption. However, the effects of changes in this assumption can be estimated from the model sensitivity to changes in this cost characteristic. For armored LCVs in general it appears that a 50% change in cost per unit power has a 20-25% impact on

*Since a turbine runs at higher speed than an equivalent-power diesel, reduction gears are built into the engine to reduce its output rpm. In this analysis, this gearing is included as part of the transmission.

(platform) cost per unit payload (Section II-B-3). Thus it can be inferred that propulsion system costs are themselves an important factor in evaluating advances in propulsion systems for these vehicles. By way of contrast, it will be shown later that this is not the case for high-speed ships.

b. High-Speed Ships

(1) Gas Turbine Engine/Waterjet Thruster. Subsystem goals and relative payoffs are shown in the following table (see Section III-D-3). Specific volume is of minor importance in this application and is not shown.

Subsystem Type	Subsystem Parameter	Units	Current Value	Suitable Goals	Relative Payoff ($\Sigma = 1$)
Turbine	sfc_e	lb/hp-hr	0.55	0.35	0.78
	sw_e	lb/hp	0.52	1.95	(0.08)
Waterjet Thruster*	η_{xt}	--	0.48	0.53	0.27
	sw_{xt}	lb/hp	8.42	6.9	0.03

*Including reduction gears.

These results give the origin of the *increase* in specific weight indicated by the suitable system goals shown in Fig. S-3. The goals given in the table call for a highly regenerated turbine engine with a large increase in its specific weight, but much more efficient, as indicated by the much lower sfc. This gives a net benefit, since the saving in fuel weight more than compensates for the heavier engine in this application.

The emphasis on efficiency is also apparent in the goals for the waterjet thruster. There is little payoff in reducing weight, far more payoff in increasing efficiency. Between the two subsystems, as with the armored LCVs, the higher payoffs are associated with reaching the engine goals.

The technology goals associated with the improved subsystems are as follows:

For the gas turbine engine (Section IV-A-4):

- Improved ideal cycle performance to a level of 72% thermal efficiency; a highly regenerated engine operating at a maximum temperature of about 2700°F is indicated (P1).
- Maintenance of component loss levels at current best levels (P2).
- Maintenance of component specific weights at current levels, the heat exchanger being of particular importance (P1).

Even more than in land-vehicle applications, any fundamental improvements in part-power performance or in specific weight reduction of heat exchangers can be used to alleviate the maximum temperature required.

For the waterjet thruster (Section IV-C-2):

- Reduction of the sum of inlet drag losses, internal ducting losses, and pump losses by one-third. This translates into a 5-6% increase in propulsion efficiency (P1).
- Modest reductions in weight of components through better design or improved materials (P2).

(2) Closed Brayton-Cycle Engine/Waterjet Thruster. Suitable subsystem goals and relative payoffs are shown in the following table (Section III-D-3).

Subsystem Type	Subsystem Parameter	Units	Current Value	Suitable Goals	Relative Payoff ($\Sigma = 1$)
Closed Brayton	sfc_e	lb/hp-hr	0.36	0.29	0.26
	sw_e	lb/hp	15.0	6.0	0.52
Waterjet	η_{xt}	--	0.50	0.53	0.16
	sw_{xt}	lb/hp	10.1	7.6	0.07

If the current values in the table are compared to the previous table, it will be seen that the current closed Brayton-cycle engine is far heavier but also far more efficient than the gas turbine engine. It is not surprising, therefore, that the biggest payoff here is in weight reduction of the engine.

It is also interesting to note that the goals for the waterjet thruster are about the same, whether used with the closed Brayton-cycle engine or the gas turbine engine, but the current value for use with the closed Brayton-cycle engine indicates a heavier, more efficient thruster than for the gas turbine engine. The reason for this is that different points on the current technology curve are used to match the different engines. For the closed Brayton cycle it is currently profitable to get greater thruster efficiency at the expense of thruster weight, since there is an associated reduction in the engine size.

As in all other examples, in comparing subsystems, the largest payoffs are associated with engine improvements. The technology advances needed to attain the goals shown in the table are as follows.

For the closed Brayton-cycle engine (Section IV-A-5):

- Improved ideal cycle performance to a level of 71% thermal efficiency; a highly regenerated engine operating in helium at a maximum cycle temperature of 2200°F is indicated (P1).
- Maintenance of component loss levels at current best values (P2).
- Reduction of heat exchanger specific weight: the regenerator by 40%, the cooler by a factor of 2-2.5, the heater by a factor of 3. Small passage sizes, lightweight materials, and a maximum heater temperature of about 3600°F are indicated (P1).

For the waterjet thruster, the goals and technology advances needed are the same as when it is used with the gas turbine engine.

(3) Propulsion System Cost Considerations. As noted above for LCVs, the effect of changes in the cost per unit power of the propulsion system can be estimated (Section II-D-2). The results show that to give a 20-25% impact on cost per unit payload, propulsion system cost per unit power would have to change by roughly a factor of four. The implication is that propulsion system costs are in themselves not nearly as important as they are, for example, in armored LCVs.

4. Potential Limits for Other Subsystems that were Studied

a. Otto and Stirling Engines. For *Otto* and *Stirling* engines, no suitable goals are developed here, since the assessments of the potential limits of technology did not indicate that a sufficiently large impact on the vehicle classes studied could be obtained. These assessments (as shown in Fig. S-4) do indicate, however, that substantial performance improvements are within the limits of possibility. In the vehicle applications considered here, the inherent limit (compression ratio) on the ideal performance of the conventional Otto (carbureted) produces a relatively high specific fuel consumption with attendant penalties that cannot be overcome by weight or possible cost advantages: compound, adiabatic, and stratified-charge spark-ignition engines operating at compression ratios of greater than 12 are considered indistinguishable from similar advanced Diesel engines and are included as Diesel engines; Stirling engines are governed by the large amount of internal energy transfer required in the engine, and the resulting relatively large weight and size cannot be balanced by the relatively low specific fuel consumption in the low-power-level vehicles to which the engine is constrained.

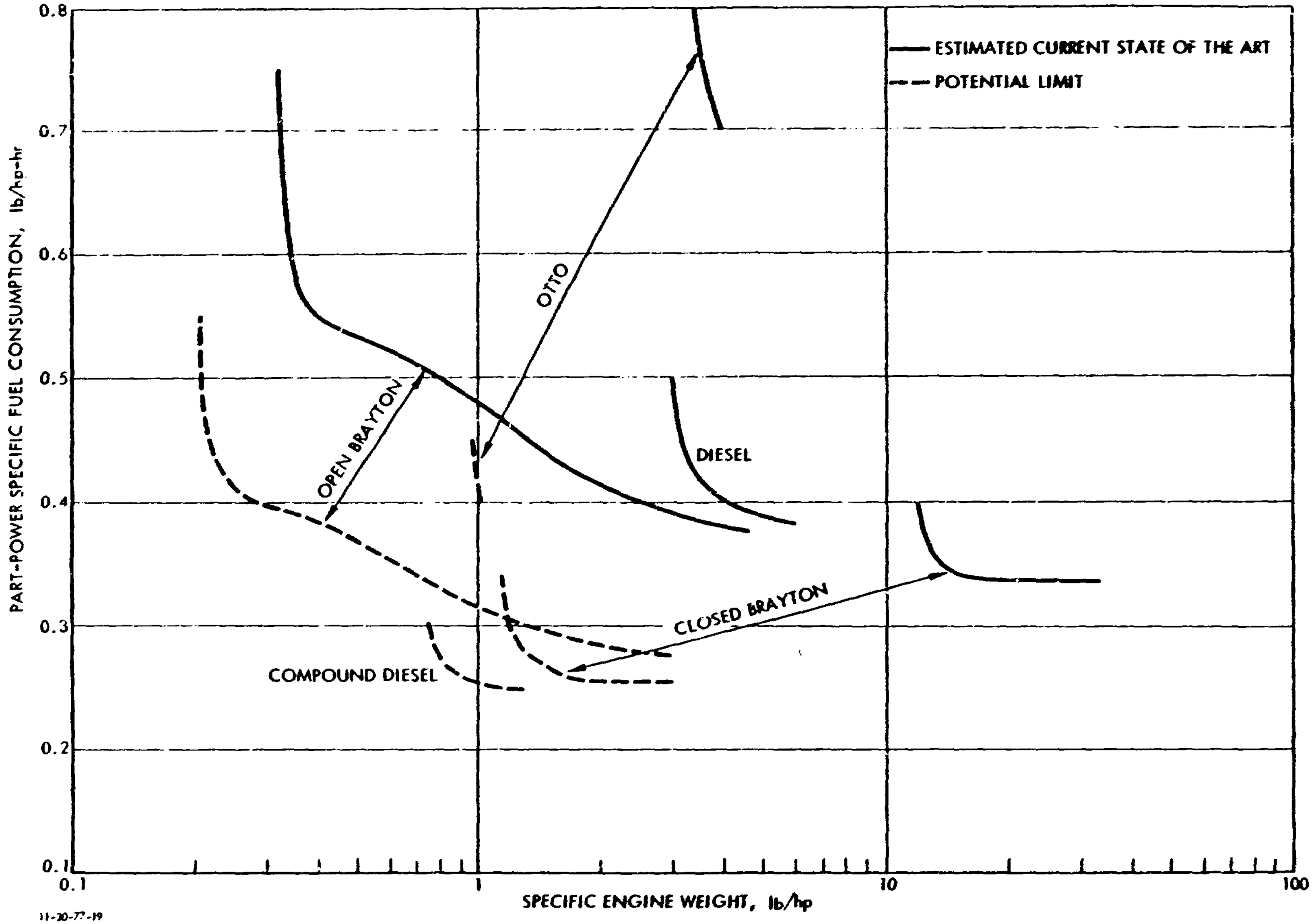


FIGURE S-4. Estimated state-of-the-art and potential-limit performance of some types of heat engines. Nominal power levels: Otto--20 hp/cyl unsupercharged; Diesel--50 hp/cyl unsupercharged; open and closed Brayton--10,000 hp.

b. <u>Mechanical, Hydromechanical, and Electrical Transmissions</u>. The scope for improvement in the size and efficiency of the transmission subsystems that were studied is less than for engines. Much of the projected gain in engine performance parameters is due to the improvement in ideal efficiency attained at higher temperatures, and this avenue is not open to transmissions whose ideal efficiency is 100%. Thus, the avenues for improvement are either (1) in efficiency through reduced losses or (2) in weight through design and material advances. It is judged in this study, for the particular subsystems examined, that the scope for further improvements in these areas is limited, as discussed below.

(1) <u>Mechanical Transmissions</u>. Significant improvements in mechanical transmissions can only be expected in weight reduction, since losses are already so small that further loss reduction is not significant. Thus unlike the other subsystems, efficiency is not a function of size. There is little chance that size reductions will come from new innovative designs, since there has been so much work done in this area. Future size reductions are most likely to come from improvements in material properties. Potential limits were estimated at 40% in size reduction.

(2) <u>Hydromechanical Transmissions</u>. The study considered hydrodynamic tank transmissions in some detail. In general, for the mechanical part of the transmission (about two-thirds of the weight), the above remarks on mechanical transmissions apply, i.e., further significant technology advances will come through weight reduction by use of improved materials. For the fluid-mechanical energy conversion elements (about one-third of the weight), the goal is to reduce losses while maintaining weight. The results of this kind of tradeoff are shown in Fig. S-5.

A similar situation exists in hydromechanical transmissions (e.g., such as the HMPT-500 developed for the MICV). That is,

the larger part of the system is mechanical, and the smaller part involves fluid-mechanical energy transfer. One can expect weight reduction largely in the mechanical part and efficiency improvement largely in the fluid-mechanical part. Thus, the potential effects of technology advances are similar to those shown in Fig. S-5.

(3) Electrical Transmissions. The elements of an electrical transmission are taken to be electromechanical conversion devices (i.e., a generator and a motor), current switching apparatus, and distribution cabling. It is found that the size and efficiency are dominated by the electromechanical conversion devices. With conventional electrical machinery, these components are too heavy for the military applications of interest. Potential limits were not established in this area, but there are some innovative approaches that should be explored further. One is to reduce the efficiency of the converters and provide cooling. This is done in some aircraft equipment with remarkable size reductions. Other approaches are the SEGMAG machines and superconducting machines. All of these approaches will result in loss of efficiency, but if the estimated weight reductions by factors of 3 to 6 are attained, electrical transmissions could become competitive. This area is the subject of a further study by IDA for DARPA.

c. Thrusters. Thrusters, like transmissions, have less scope for improved weight and efficiency characteristics than engines, since again the avenue of significantly improved ideal efficiency is not open. In land-vehicle thrusters, the ideal efficiency is determined by the slip, which depends primarily on the ground pressure and the length of thruster in the direction of motion for a given thrust load. In thrusters for high-speed ships, the ideal efficiency is limited by the practical size of the thruster to roughly 70-75%, as indicated in Fig. S-6. In addition to the tracks and waterjet thrusters described above, wheels and supercavitating propellers were also examined.

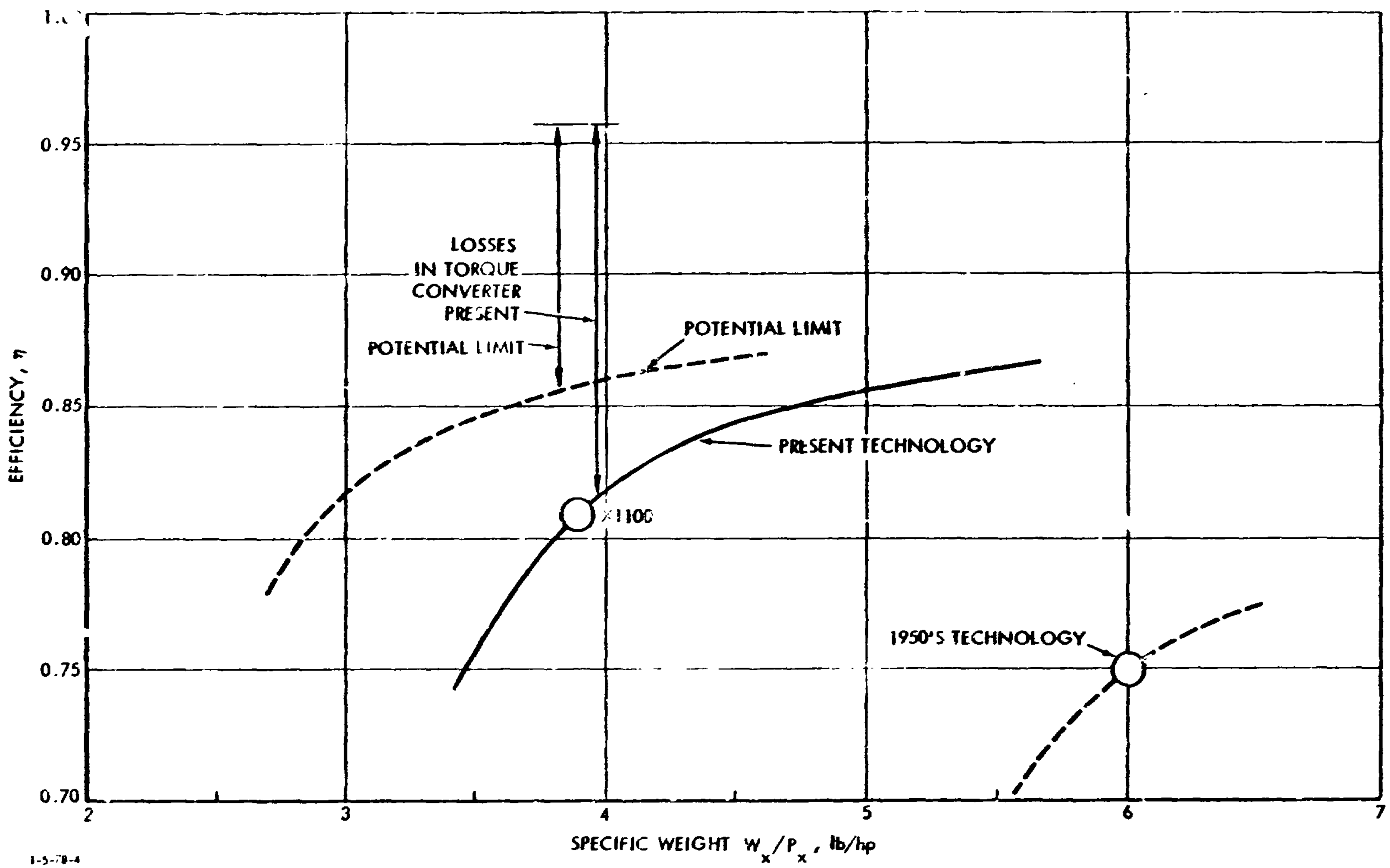


FIGURE S-5. Efficiency and specific weight characteristics of a hydrodynamic transmission unit for an MBT.

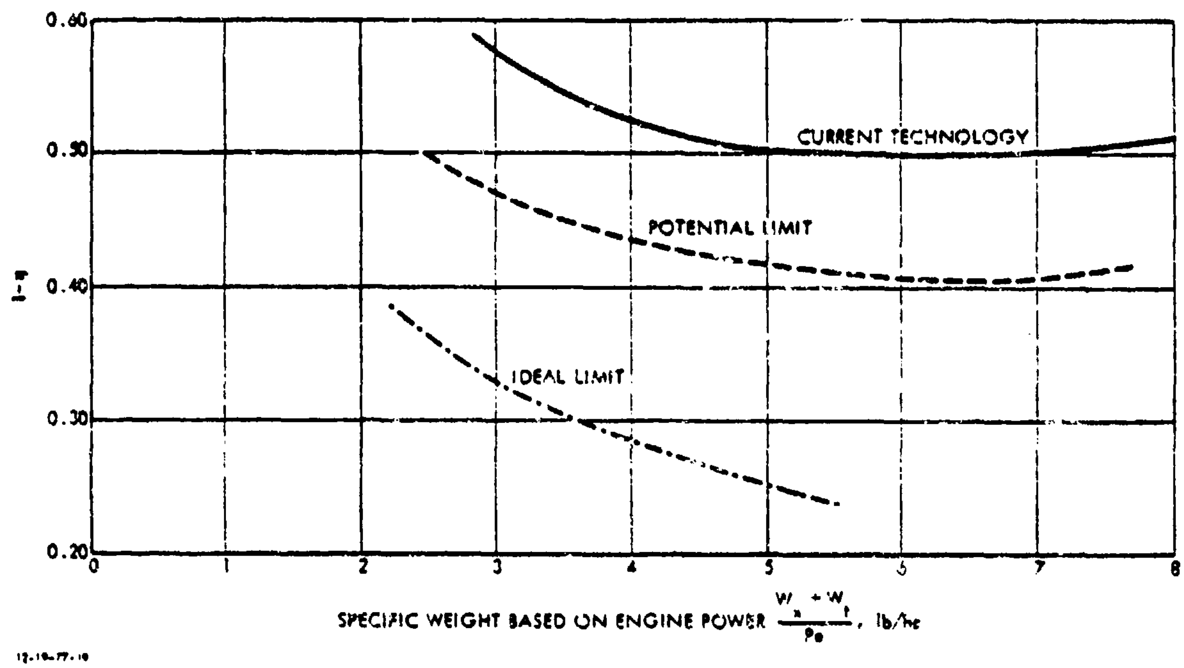


FIGURE S-6. Efficiency and specific weight characteristics for a mechanical transmission/waterjet combination. Reference condition: 20,000 shaft horsepower.

(1) Wheels. A comparison of wheels and tracks (made in Appendix K) shows that the size of wheels alone makes them unattractive for military combat vehicles at gross vehicle weights (GVWs) above about 25 tons. When the complexities of all-wheel drives are added, it is estimated that the tradeoff position drops to GVWs of about 15 tons. On a weight and size basis, therefore, wheels are found to be an option only for the lightest armored LCVs.

(2) Supercavitating Propellers. On a straight comparison between thrusters, supercavitating propellers are found to be competitive in efficiency and weight with waterjet thrusters. When combined with a transmission, however, the waterjet thruster wins out because its pump can be closely coupled to the engine, whereas the propeller requires transmitting power some distance, and in the SES design, also right-angle changes in direction.

It should be noted that development of a competitively sized electrical transmission could change this situation with respect to both wheels and supercavitating propellers.

I. INTRODUCTION

A. BACKGROUND

This study resulted from a desire by DARPA to identify those areas of propulsion technology where advances would have potentially large payoffs for military surface vehicles using conventional fuels. There is no lack of specific new ideas in engines, transmissions, or thrusters for these applications. Some current examples include: ceramics to allow higher temperatures in engines; closed-cycle systems for propulsion engines; electrical transmissions with or without superconducting elements; compliant wheels instead of tracks for some types of off-road combat vehicles; and waterjets for propulsion of Navy escort vessels. DARPA is constantly involved in both soliciting and evaluating ideas like these with a view to funding high-risk, high-payoff projects. In examining the virtue of such new approaches, questions naturally arise regarding both the risks and the payoffs, such as "which ideas have payoffs high enough to be interesting" and "are there potential high-payoff areas in which more ideas should be solicited?" The general purpose of this study is to develop information that can aid in answering such questions.

A number of questions of a different kind can be raised concerning the appropriateness of both the subject matter and the purpose of such a study. The apparent mature state of propulsion system technology and a common feeling that potential payoffs in propulsion systems are considerably less than those in other areas, most notably offensive and defensive armament, foster questions regarding the subject matter of the study.

Concerns with the relative importance of risk evaluation foster questions regarding the purpose of the study. A brief discussion of such questions seems in order here.

A question following from the common belief that propulsion systems have matured in their development is whether there is much fertile ground left to plow. In this connection, it is interesting to note that only about one-sixth of the energy stored in the fuel is converted into thrust energy in the vehicles of interest--a fraction which seems far removed from any overall physical limit such as, for example, the Second Law of Thermodynamics. In addition, at least qualitatively, potential prospects exist for advancing the state of the art toward such physical limits, including:

1. New concepts in the form of different syntheses of the well-known forms of energy conversion (compression, expansion, energy addition, heat exchange, power transmission, and thrust production).
2. Reduction of the losses associated with energy conversion processes. Traditionally, advances in this area have not been pursued on their own merit.
3. Reductions in the weight and volume of energy conversion equipment. Traditionally, advances in this area have been pursued vigorously.

This study addresses the quantitative prospects for advances in these areas by examining the relationships between the propulsion system design parameters for relevant equipment and the physical processes involved, in order to identify, where possible, physical limits relative to the current state of the art.

Other questions regarding the general prospects of payoffs in propulsion system advances arise from the observations that in re[illegible]t years the greatest improvements in combat vehicles have originated from improved offensive and defensive armament systems, which do not always require new vehicles, and that

potential exists for still further improvements, particularly in precision-guided munitions. A common feeling, then, is that even if improvements in propulsion systems are possible, they may be too expensive to get into service, particularly if they require new vehicles, and may have much less impact than the armament system improvements.

On the other hand, it can be speculated that improvements by potential enemies in precision-guided munitions will necessitate new types of surface vehicles--specifically, smaller ones--and thus the opportunities for getting improved propulsion systems into service will be greater than in the past. More importantly, perhaps, the impact of propulsion system improvements on the size and cost of combat vehicles is larger than sometimes realized. The surface combat vehicles of interest in this study are all high powered, to the point that the size of the propulsion system is roughly equal to the size of the combat payload. In this situation it is easy to show that for the same vehicle performance, a reduction in propulsion system size (for the same output) reflects directly in a reduction in vehicle size; e.g., a 10% reduction in propulsion system size will give a 10% reduction in the size of the entire vehicle and an associated reduction in platform cost. This results, of course, from the fact that with a smaller propulsion system the whole vehicle can be built smaller and still accommodate the same payload and give the same performance with less installed power. This study addresses these matters by evaluating the impact of propulsion system size on the size and cost of selected classes of vehicles and comparing this with the possible impact of technology advances on propulsion system size.

A final question as to the appropriateness of the purpose of the study--in particular, its focus on potential payoffs--arises from a view that the payoffs associated with technology advances are in general adequate and also difficult to quantify, and hence that study of the risks involved and resources required is more productive than study of the payoffs. The view adopted

here, however, is that since some potential technology advances obviously have higher payoffs than others, it is important to know these payoffs in order to formulate appropriate goals. This is not intended to minimize the importance of risk assessment; indeed, this study partially addresses risks by examining the degree to which technology advances approach the physical limits to which propulsion system technology is inevitably constrained.

B. PURPOSE AND SCOPE

This study is in response to DARPA Project Assignment A-40 (included as Appendix M). The primary purposes of the study are to:

1. Quantify the technological advances needed to make major improvements in military propulsion systems
2. Provide criteria for the evaluation of new propulsion system or subsystem concepts.

A propulsion system is defined here to include the three major subsystems necessary to deliver thrust to a vehicle: an engine, a transmission, and a thruster. The scope of the study is limited to an assessment of propulsion systems for four classes of surface combat vehicles: (1) main battle tanks; (2) light, tracked land combat vehicles; (3) high-mobility land combat vehicles; and (4) high-speed (>50-knot) ships. These classes generally cover the spectrum of surface combat vehicles, with the important exception of conventional major naval surface combatants (aircraft carriers and destroyers, primarily). For propulsion subsystems, five engine types (Otto, Diesel, gas turbine, closed Brayton, Stirling), three transmission types (mechanical, hydrodynamic/hydromechanical, electrical), and four thruster types (tracks, wheels, propellers, waterjets) are examined in some detail. These subsystem types include most of those that have been used or are being considered for the subject

vehicle classes; in addition, prospects for innovation are addressed by consideration of needed subsystem characteristics without regard to specific type. Finally, as mentioned earlier, criteria for the evaluation of new propulsion systems or subsystems are limited to considerations of potential payoff and physical possibility; matters relating to the resources required to achieve a needed technological advance or to specific risks involved are not within the scope of the present study.

C. APPROACH

1. Nature of the Problem

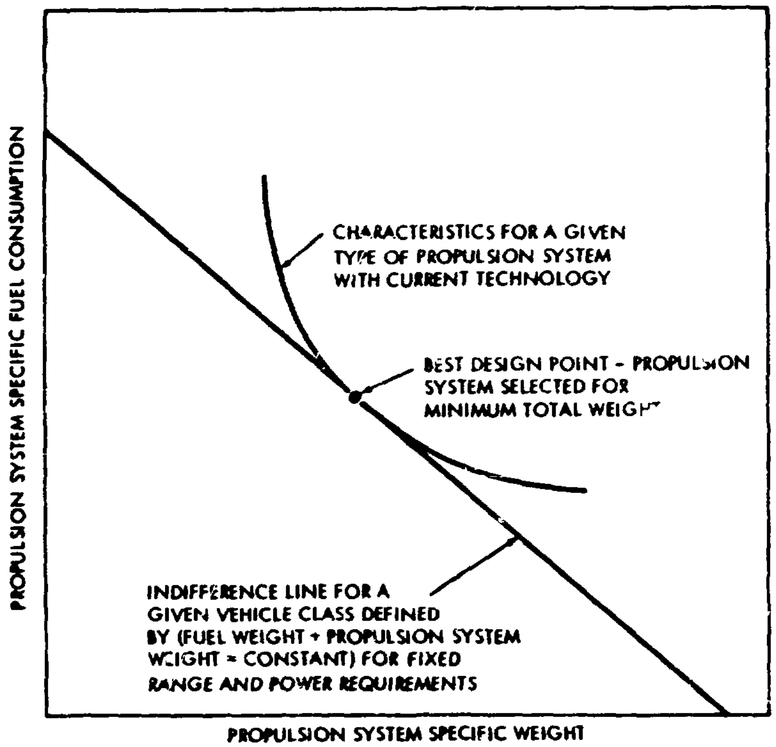
The task of quantifying the technological advances needed to make major improvements in military propulsion systems is of course one that contains inherent difficulties. First, propulsion system technology is generally, and usefully, characterized by a variety of design parameters (e.g., specific fuel consumption at various power levels, specific weight, noise level). It is not feasible here to examine the possible improvements in all such characteristics, nor are they all of equal importance; hence the parameters which seem of most importance must be selected. Second, a means of measuring the impact of major improvements in military propulsion systems must be established. This involves selecting a suitable measure and setting a criterion as to the magnitude of change that constitutes a major improvement. Third, improvements in propulsion system technology, however characterized, originate from both the interactions among the three major subsystems and improvements in subsystem technology, the latter of which in turn originate from improvements in constituent components and related physical processes (e.g., compression, expansion, heat exchange). Thus, both subsystem and related component/process technology require consideration. Finally, a "needed technology advance," if it is not to be pie-in-the-sky, should be within the bounds of physical and practical possibility; hence, some attention to these bounds is required.

Further, a technology advance needed to achieve some overall impact is likely to have as many dimensions as there are technological characteristics; some attention to the balance among such characteristics is accordingly required.

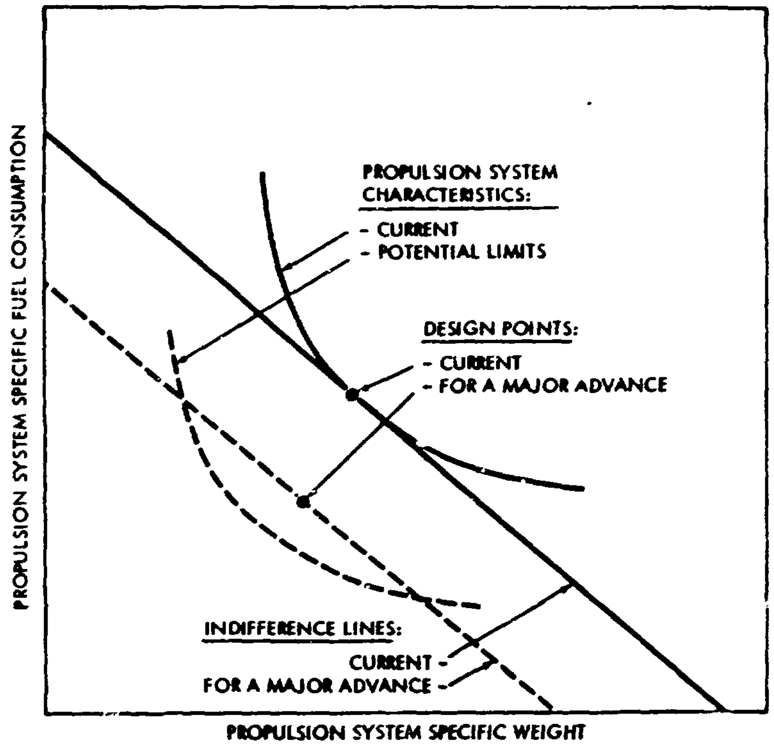
Evidently, then, any approach to the task entails basic decisions regarding the form of propulsion system technology characteristics, the measure of the impact of technology improvements, estimates of potential physical limits, and statements of needed technology advances, as well as an analysis procedure by which appropriate connections can be made. These decisions as made in this study are discussed in the subsequent paragraphs. Before proceeding to these discussions, however, a brief overview of the basic concept of the analysis used here is appropriate.

2. Conceptual Basis of the Analysis

The basis of the analysis is to compare the size and efficiency characteristics of given propulsion systems (i.e., engine-transmission-thruster combinations) with those characteristics needed to meet constraints imposed by the vehicle characteristics. As an illustr[illegible] exar[illegible]e, consider a case where a vehicle is constrained [illegible] specified maximum weight, and further assume that the only propulsion system characteristics which influence vehicle weight are the specific fuel consumption and specific power (weight per unit power). Conceptually, the comparison between the propulsion system characteristics needed by the vehicle and those provided by a given type of propulsion is as shown in Fig. I-1a. In this [illegible]ure the vehicle indifference line represents the trade[illegible] between fuel and propulsion system that keeps the sum of their weights constant for given power and range requirements, and hence it defines parameter values that give no first-order impact on [illegible] vehicle. The propulsion system characteristics line in [illegible]g. I-1a represents the tradeoff between weight and efficiency that is always possible in power



a. Matching current propulsion system and vehicle characteristics.



b. Projecting characteristics required for a major advance.

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FIGURE I-1. Conceptual basis for establishing propulsion system characteristics needed to make a major advance in a specific vehicle application.

conversion devices at a given state of technology. The tangent point of the two lines is obviously the optimum design point--the point where the propulsion system characteristics available match those needed at a minimum vehicle weight.

What is done in this analysis is to look for a new design point by defining how far the vehicle indifference line must be shifted to have a major impact on the vehicle, and how far the propulsion system characteristics curve may be shifted before reaching its potential physical or practical limits. If a new design point can be found, as shown conceptually in Fig. I-1b for our illustrative example, this establishes "major advance" goals for a given propulsion system in a given vehicle class. This procedure is used to decide which specific propulsion systems have the potential for contributing a major advance and to set goals for those that do. The system goals are then used to establish a set of subsystem goals and a related set of technology advances.

3. Performance Characteristics of Propulsion Systems

This study is limited to consideration of specific weight, specific volume, and specific fuel consumption as the propulsion system performance characteristics of primary concern. The rationale for selecting these parameters as basic is that the primary criterion of acceptability in a vehicle design is that fuel, propulsion system, and payload are accommodated in the weight and volume available in a suitable vehicle with sufficient power. Only if a proposed system passes this size and efficiency test are other characteristics such as noise and exhaust signature of importance. While potential improvements in these other characteristics may well have an impact on system cost-effectiveness, the judgment here is that the basic characteristics selected merit first attention.

Consideration of the operating conditions to which specific weight, specific volume, and specific power are referenced is

required. Specific weight and specific volume are referenced to the maximum power condition, since this combination determines the weight and space consumed by the propulsion system. The fuel consumed by the propulsion system is, however, a function of the duty cycle of the vehicle--the time spent at various power settings in actual use. The uniform characteristic of the duty cycles of the vehicles considered here is that a large fraction of time is spent at cruise or other low-power conditions, although specific details of duty cycles are subject to considerable variation. Unfortunately, the specific fuel consumption of some types of propulsion systems is sensitive to power level, particularly at low power, and hence the total fuel required to obtain a given vehicle range can be sensitive to the details of the specified duty cycle. Rather than become enmeshed in such matters, for the comparisons to be made here it is assumed that the 25% power condition is a reasonable single-value representation of the duty cycle for the vehicles considered, and hence the specific fuel consumption of interest is that at 25% power.

4. A Measure of Propulsion System Impact

Evaluating the impact of propulsion system improvements on a weapons system can be a treacherous proposition. Consider, for example, the impact an improvement in specific fuel consumption (SFC) can have on a given vehicle. For the same vehicle size or cost, the vehicle range could be increased at no detriment to the payload or vehicle speed, and an appropriate impact measure would be the fractional increase in range so obtained; or the payload could be increased at no detriment to vehicle range or speed, and an appropriate measure would be the fractional increase in payload; or the vehicle speed could be increased at no detriment to vehicle range or payload, and an appropriate measure would be the fractional increase in speed. Alternatively, for the same vehicle speed, range, and payload, the vehicle size or cost could be decreased, and an appropriate

measure would be the fractional size reduction or the fractional cost reduction. Thus, benefits for this single improvement could be measured in many different ways.

Further, both the absolute and relative magnitudes of these alternative measures depend upon the characteristics of the given vehicle. For example, consider the impact an SFC improvement would have in two different vehicles--a long-range vehicle carrying a relatively large amount of fuel and a relatively small payload, and a short-range vehicle carrying relatively little fuel and a relatively large payload. A given SFC improvement, if used solely for range improvement, would produce identical fractional increases in range in the two vehicles; however, if it is used solely for increasing payload, it would produce a far greater fractional increase in payload in the long-range vehicle than in the short-range vehicle.

To resolve these difficulties, the measure of propulsion system improvements used here is the resulting reduction in cost* per unit payload in carefully selected reference vehicles, at fixed performance.** One advantage of this measure is that, in our opinion, it can be viewed as a crude indicator of the change in vehicle cost-effectiveness, insofar as the payload of a vehicle with fixed performance characteristics can be viewed as an indicator of vehicle effectiveness. In this respect, the measure seems superior to simpler possible measures, such as vehicle weight per unit payload. The measure does not, of course, imply that the only use of propulsion system improvements is in vehicle cost reduction. Indeed, propulsion system improvements have been historically used to improve vehicle performance (i.e.,

*Vehicle costs are defined here as the procurement and direct operation and maintenance costs over an appropriate life for the entire vehicle, exclusive of its combat payload costs.

**Fuller discussion of this subject is given in D.M. Dix and F.R. Riddell, "Projecting Cost-Performance Tradeoffs for Military Vehicles," *Aeronautics and Astronautics*, September 1976.

speed or range) rather than reduce vehicle cost per unit payload. In such instances, the measure used here can be interpreted to first order as the difference in cost per unit payload between two improved-performance vehicles, one using the improved propulsion system and the other using the older technology. Thus, as a means of judging the impact of propulsion system improvements, the measure retains its validity.

Another advantage of the use of cost per unit payload is that it enables the potential importance of propulsion system cost characteristics to be assessed on the same basis as performance characteristics. That is, quantitative estimates can be made of whether a reduction in propulsion system costs in themselves could possibly represent a high-payoff R&D area, with or without concurrent improvements in performance characteristics. We make use of this feature here. Propulsion system costs are characterized by specific procurement cost (procurement cost per unit power) and specific maintenance cost (direct operating and maintenance cost per unit power over a 20-year life). In general, it is assumed that these cost parameters for a specific type of propulsion system are unaffected by improved performance characteristics, which seems to be in agreement with historical data. No attempt is made here to examine the prospects for reductions of these costs or the potential limits on such reductions; however, the sensitivity of vehicle cost per unit payload to changes in these propulsion system specific costs is used to assess their possible importance.

A major disadvantage of the use of cost in the measure of impact, as opposed to, say, vehicle weight, is of course the empirical and variable nature of cost data. Fortunately, for our purposes, high accuracy is not required. Further, in the absence of changes in the specific cost factors, the reduction in vehicle cost per unit payload achieved by a given propulsion system performance improvement will be approximately the same

as the reduction in vehicle weight per unit payload achieved by the same propulsion system improvement.

It is evident that the vehicle characteristics have a large influence on the resulting impact of any propulsion system improvement. A common pitfall is to consider postulated vehicles that favor particular propulsion system improvements without regard to the likelihood of military use; for example, the impact of SFC on cost per unit payload can be made as large as desired merely by postulating a longer range requirement. We endeavor to avoid this pitfall here by using, for each class of vehicle, vehicle characteristics that are representative of actual military vehicles in service at the present time. Such vehicles are referred to here as "rational" vehicles; they have had the benefit of successfully surviving a complex optimization process involving cost, performance, and value and should accordingly provide a reasonable basis for evaluating impact.

5. Evaluation of Potential Technological Limits

As indicated earlier, some estimates of potential physical or practical limits to the performance of propulsion systems are needed. This is accomplished here for each individual subsystem type by an examination of the energy transfer processes it performs and the components it uses to carry out such processes. This level of component/process seems to be the only level at which reasonable connections to the physical origins can be made, and it is also the level that is generally common to all subsystem types.

A variety of types of each individual subsystem are examined, so as to avoid the common pitfall of comparing an advanced-technology subsystem of one type to a current-technology subsystem of another type and then attempting to infer which type of subsystem has the greater potential.

It is important to emphasize that the limits estimated here are of the nature of what may be possible, or at least not

demonstrably impossible. No implication should be drawn that the path to reaching these limits is ultimately achievable. Such limits are obviously both uncertain and in part judgmental. We believe that they are reasonably representative of the actual state of affairs; nevertheless, they should not be interpreted too rigidly.

6. Suitable Goals and Relative Payoffs

The technology advances needed to make major improvements in military propulsion systems are stated here in terms of sets of "suitable goals" for propulsion system performance characteristics for each vehicle class (for example, values of specific weight, specific volume, and specific fuel consumption for a propulsion system consisting of a diesel engine, a hydrodynamic transmission, and tracks to be used in main battle tanks). Corresponding sets of suitable goals for individual subsystems and constituent energy transfer components/processes are derived from these overall goals.

Such suitable goals are defined here by three criteria. First, a set of suitable goals, if achieved, would have a major impact on the cost per unit payload of the relevant vehicle class; the general criterion for a major impact is a minimum of 20-25% reduction, which seems to be in accord with the DARPA mission of conducting high-payoff (and high-risk) research and development. Obviously, a different criterion would produce different goals. Second, suitable goals do not exceed the potential limits of improvement as estimated in this study; this means of course that propulsion system types that do not have an estimated capability that meets the major-impact criterion are not considered appropriate to that class. Third, all goals of a set are estimated to be of approximately equal difficulty to achieve; the criterion used is that the goals for all relevant characteristics represent equal fractional improvements between their current state-of-the-art values and their estimated limits.

The goals defined by these criteria are of course applicable only to a specified class of vehicle and type of propulsion system, and in all cases they presume no changes in propulsion system specific costs.

Inasmuch as such goals, due to the various uncertainties involved, can only be viewed as approximate, some guide as to the contribution of improvements in individual characteristics is appropriate. This is accomplished here by determining the payoff, in terms of change in cost per unit payload, for each individual goal.

D. ANALYSIS PROCEDURE

The essential elements of the approach, as discussed above, requires an analysis that: (1) relates vehicle characteristics to propulsion system characteristics, which is referred to here as the vehicle analysis; (2) relates propulsion system characteristics to the individual subsystem characteristics, which is referred to here as the propulsion system analysis; and (3) relates subsystem characteristics to constituent energy-transfer components and processes, which is referred to here as the subsystem analysis. Further, since both current state-of-the-art characteristics and potential limits of propulsion systems originate with components and processes, while their impact originates with the vehicle, each level of analysis contains two paths. The resulting analysis procedure is shown schematically in Fig. I-2.

The analysis begins with an assessment of the current state-of-the-art and potential limits of component/process characteristics (lower right of Fig. I-2), which are used in the subsystem analysis to develop corresponding subsystem characteristics, which are in turn used in the propulsion system analysis to develop corresponding propulsion system characteristics, which are in turn used in the vehicle analysis, in conjunction with

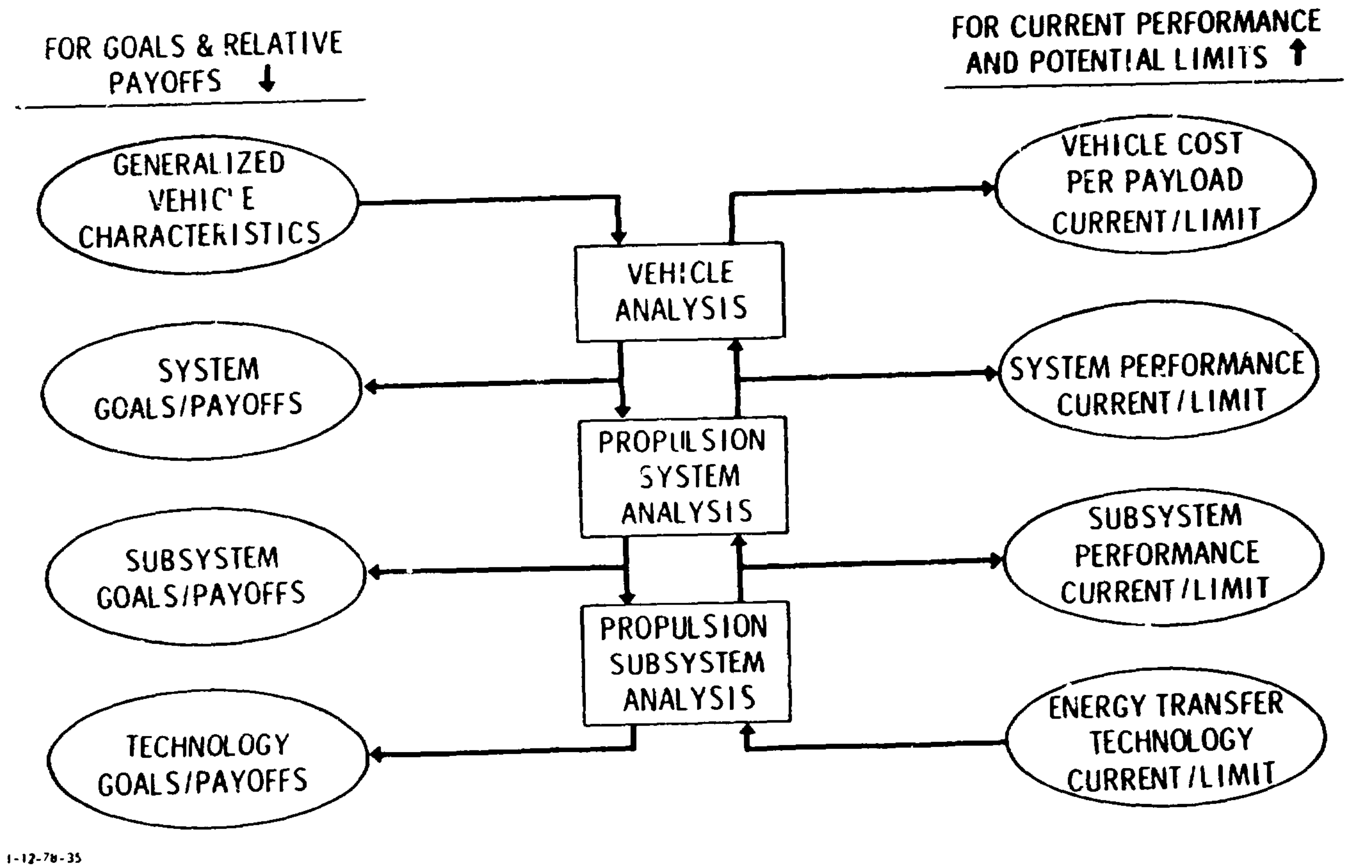

FIGURE I-2. Elements of analysis.

generalized vehicle characteristics (upper left of Fig. I-2), to develop corresponding state-of-the-art and potential limits on vehicle cost per unit payload. Then, using the criterion of significant impact on vehicle cost per unit payload, propulsion system goals and relative payoffs are developed in the vehicle analysis, subsystem goals and relative payoffs are developed in the propulsion system analysis, and component/process goals and relative payoffs are developed in the subsystem analysis. In particular, by considering the interactions among the individual subsystems in the propulsion system analysis, the procedure seeks to avoid the common pitfall of overlooking such interactions, which, as will be seen, can be important.

What emerges from the analysis, then, is essentially a hierarchy of goals and relative payoffs for (1) propulsion systems for each vehicle class, (2) propulsion subsystems for each propulsion system type and vehicle class, and (3) subsystem energy transfer processes and components for appropriate subsystems. It is believed that these goals and relative payoffs, in conjunction with the state-of-the-art and potential limits which also emerge from the study, provide a framework by which any propulsion system or subsystem concept can be evaluated relative to the specific vehicle classes considered.

E. ORGANIZATION OF PAPER

The organization of the paper is based on the three levels of analysis depicted in Fig. I-2. Section II deals with the vehicle analysis, and hence vehicle characteristics for each specific vehicle class are defined and related to state-of-the-art characteristics and potential limits of propulsion systems, in order to develop suitable propulsion system goals and relative payoffs. Section III deals with the propulsion system analysis, and hence state-of-the-art characteristics and potential limits of propulsion systems are developed, as are suitable goals and

relative payoffs for individual subsystems. Section IV deals with the subsystem analysis, and hence state-of-the-art characteristics and potential limits of both subsystems and constituent components and processes are developed here, as are suitable goals and relative payoffs for the constituent components and processes. These developments are supported by a series of appendices, authored in general by the various individual contributors to this study.

It should be noted that organization of the text in this way requires that Section II use results on state-of-the-art characteristics and potential limits developed in Section III, which in turn requires similar results developed in Section IV. This particular organization, however, is selected to reflect the framework for evaluation of any new propulsion system concept, which should logically start with an evaluation of its potential impact on the vehicle and then proceed to levels of greater detail.

II. PROPULSION SYSTEM IMPACTS ON SELECTED VEHICLE CLASSES

This section deals with the vehicle analysis shown in Fig. I-2. The objective is to establish suitable goals for the propulsion system characteristics of the four selected vehicle classes and also to show relative payoffs between individual characteristics if the goals are reached. The required inputs are (1) generalized vehicle characteristics for each class of vehicle, which are developed in Appendices A and B, and (2) propulsion system state-of-the-art characteristics and potential limits, which are developed in Section III.

Goals are established by deriving from the vehicle characteristics the improvements in propulsion system characteristics needed to make a major impact on each particular vehicle class, and then comparing what is needed with what is available as defined by the state-of-the-art characteristics and their potential limits for specific propulsion systems. Relative payoffs are established by assessing the relative contribution of each improved characteristic to the overall impact.

The basis of the analysis is presented first and is followed by results for each of the four selected vehicle classes.

A. INTERACTIONS OF PROPULSION SYSTEM AND VEHICLE IN GENERAL

1. Vehicle Indifference Lines

The vehicle and its propulsion system may be characterized as shown in Table II-1. The relationships between the vehicle and the propulsion system performance parameters and between the vehicle elements are as follows:

Elements:

Payload

Configuration

Fuel

Propulsion System

Vehicle Parameters:

Payload Weight W_L

Payload Volume ∇_L

Configuration Weight Fraction W_c/W_v

Maximum Specific Power P_{max}/W_v

Cruise Specific Power P_{cr}/W_v

Cruise Endurance E_{cr}

Procurement Cost $\$_{pv}$

Maintenance Cost $\$_{mv}$

Propulsion System Parameters:

Specific Weight $W_{ps}/P_{max} = SW_{ps}$

Specific Volume $\nabla_{ps}/P_{max} = SV_{ps}$

Specific Fuel Consumption SFC (based on P_{cr})

Specific Procurement Cost = $\$_{pp}/P_{max}$

Specific Maintenance Cost = $\$_{mp}/P_{max}$

Fuel Parameters:

Fuel Weight W_F

Fuel Volume ∇_F

where W_v = Gross Vehicle Weight

P_{max} = Maximum Thrust Power

P_{cr} = Cruise Thrust Power

W_{ps} = Propulsion System Weight

∇_{ps} = Propulsion System Volume

$$\frac{W_{ps}}{W_v} = SW_{ps}\left(\frac{P_{max}}{W_v}\right)$$

$$\frac{\nabla_{ps}}{\nabla_v} = SV_{ps}\left(\frac{P_{max}}{\nabla_v}\right)$$

$$\frac{W_F}{W_v} = SFC\ E_{cr}\left(\frac{P_{cr}}{W_v}\right)$$

$$\frac{W_F}{W_v} + \frac{W_{ps}}{W_v} + \frac{W_L}{W_v} + \frac{W_c}{W_v} = 1$$

$$\frac{\nabla_F}{\nabla_v} + \frac{\nabla_{ps}}{\nabla_v} + \frac{\nabla_L}{\nabla_v} + \frac{\nabla_c}{\nabla_v} = 1$$

To illustrate how vehicle characteristics constrain propulsion system improvements, consider that a reference design is given and the question is asked whether a new propulsion system is better than the one now used, in the sense that it could provide reduced vehicle size without sacrificing payload or performance. For the sake of simplicity, let us assume that weight rather than volume dominates the vehicle design. Using the relationships above, the total weight of the propulsion system and its fuel supply can be expressed as

$$\frac{W_F}{W_v} + \frac{W_{ps}}{W_v} = SFC\ E_{cr}\left(\frac{P_{cr}}{W_v}\right) + SW_{ps}\left(\frac{P_{max}}{W_v}\right) = 1 - \frac{W_L}{W_v} - \frac{W_c}{W_v}\ , \quad \text{(II-1)}$$

which can be plotted as in Fig. II-1 to show how the weight and efficiency characteristics of a proposed new propulsion system compare with the reference design. To impact the vehicle size

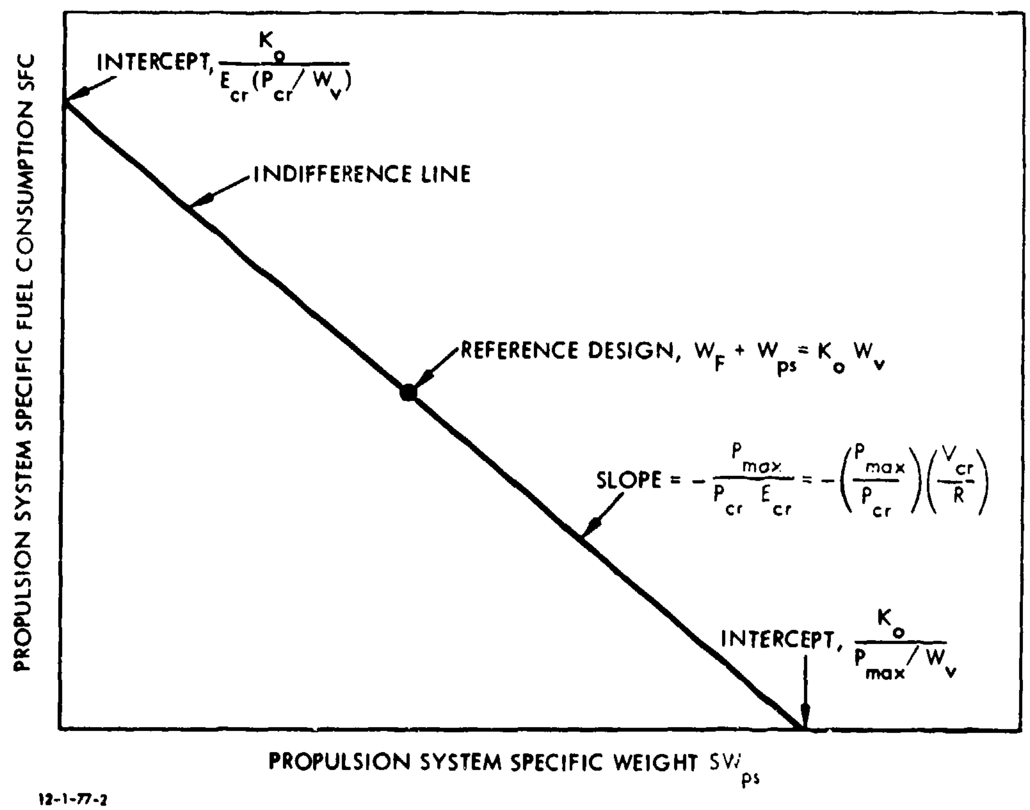

FIGURE II-1. Graphical relationship of propulsion system and vehicle characteristics. The indifference line is defined by

$$SFC\ E_{cr}\left(\frac{P_{cr}}{W_v}\right) + SW_{ps}\left(\frac{P_{max}}{W_v}\right) = K_o ,$$

where K_o = fraction of vehicle weight in propulsion system (including fuel).

favorably, a new system must fall below the "indifference line" defined by setting Eq. II-1 equal to a constant. Further, as the slope and intercepts given in Fig. II-1 indicate, the benefit of the improved propulsion system does not have to be taken in reducing vehicle size but could be used to improve performance (speed or range) or payload-carrying ability.

In these terms the impact of an improvement in propulsion system characteristics could be measured in several ways. One possible measure of benefits is potential reduction in vehicle size; however, as discussed more fully in the Introduction, the measure used in this report is potential reduction in cost per unit payload of the reference design with fixed performance characteristics. It should be noted, however, since constant performance implies that propulsion power varies as vehicle weight, and if specific costs of the propulsion system are constant, which seems to follow the historical trend, that reduction in cost per unit payload is closely approximated by proportionate reduction in weight per unit payload. Thus we can take a weight indifference line as an approximation to a cost indifference line.

2. Matching Vehicle and Propulsion System Characteristics

For a given state of technology and a given selection of subsystem types (i.e., a given type of engine, of transmission, and of thruster) the lower boundary of the range of values of SFC and SW_{ps} is in general a curve as shown in Fig. II-2 (these state-of-the-art propulsion system characteristics are developed in Section II.). Under the constraints noted above, the design optimization should lead to selection of a propulsion system with the minimum total weight demands, i.e., for this condition the envelope of possible propulsion systems is tangent to the "indifference line" at the optimized design point, as shown in Fig. II-2. Note that since the location of the indifference line depends on the mobility (i.e., power), range, and payload-

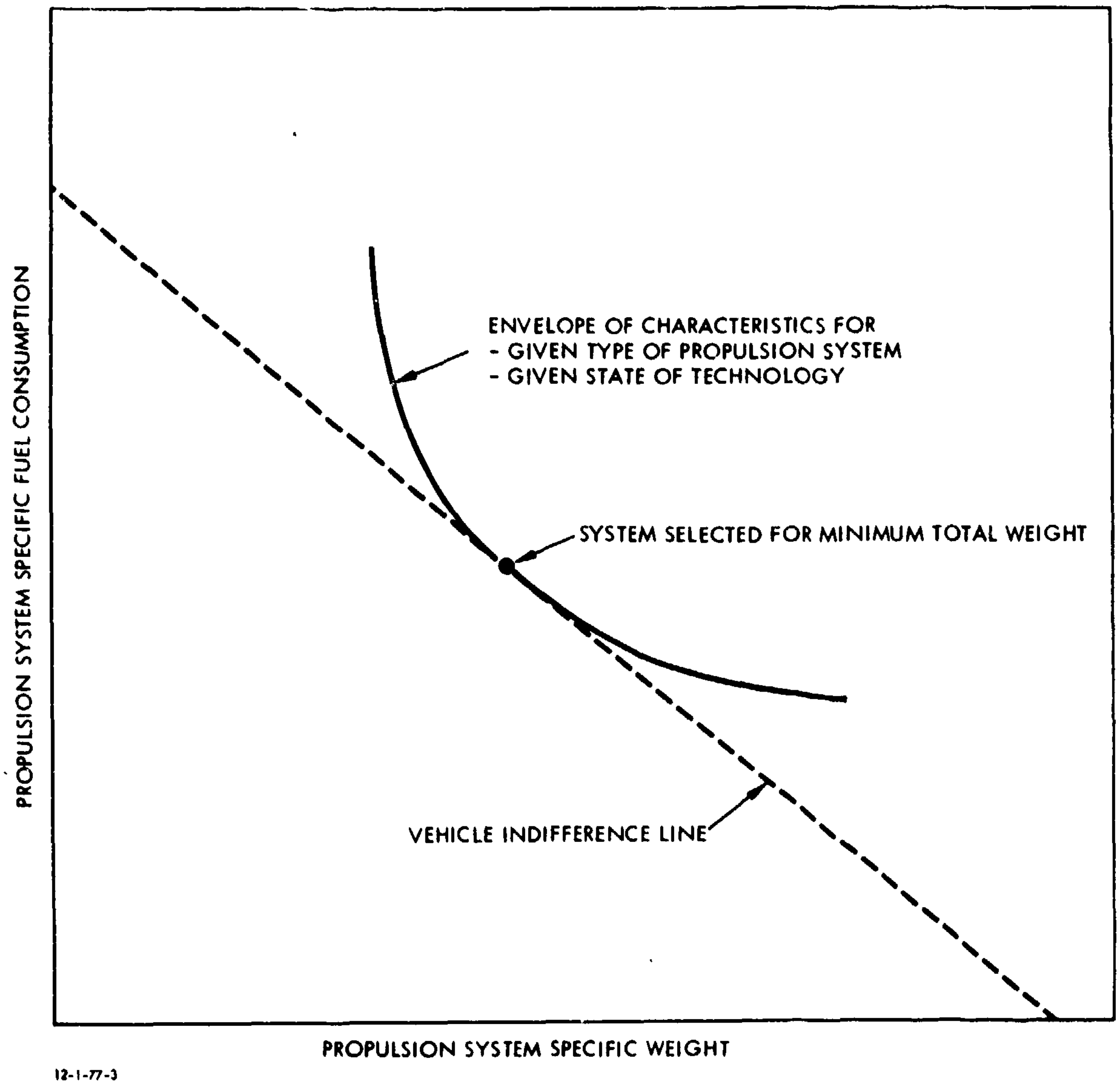

FIGURE II-2. Matching propulsion system and vehicle characteristics.

carrying specifications for the vehicle, it is possible to define a combination of these vehicle characteristics that cannot be met by available propulsion systems. In this case, design optimization must involve a modification of the vehicle specifications so that a tangent point can be found. The reference designs used in this study are derived from vehicle designs which have been through this complicated optimization process. If such a vehicle also has proven field acceptance (i.e., accepted cost-effectiveness), it is defined as a rational vehicle.

3. Goals for a Major Advance and Relative Payoffs

In these terms a major advance can be defined by a given shift in the indifference line* in Fig. II-2 and propulsion system technology goals can be set by establishing what new SFC and SW values are needed to match this new indifference line. As will be seen below, the criterion of a 20-25% reduction in cost per unit payload at constant performance is used here to define a major advance for the purpose of establishing goals for the power train in land combat vehicles. For a high-speed ship, the criterion used is reduction of the propulsion system weight fraction to historically accepted values. Such criteria are, of course, arbitrary, but were judged to be consistent with the DARPA charter of looking for high-risk, high-payoff R&D projects.

In Section III, in addition to state-of-the-art propulsion system characteristics, potential limits are established. Provided these potential limits cross the new indifference line for a major advance, a new vehicle design point can be found, and the values of SFC and SW_{ps} defined by this new design point become the propulsion system technology goals for a major advance.

*At constant performance, the indifference line shifts parellel to itself (see Fig. II-1).

Finally, the relative payoffs between the reduction in SFC and the reduction in SW_{ps} to reach this new design point can be evaluated by comparing the contribution each makes to the total reduction in cost at the new design point. This requires computing cost sensitivities for each characteristic, which will be described below.

4. Application to Specific Vehicle Classes

The approach described above can be applied directly to vehicles which are weight sensitive but not volume sensitive. This is practically the case for the high-speed oceangoing ships included in this study. However, for land combat vehicles (LCVs), modification of the approach is needed to account for the dependence of the weight of the armor on the volume of the elements it protects. It is convenient in this case to consider the propulsion system in two parts--one external to the armor (i.e., the tracks and suspension system which together are the thruster) and the other inside the armor (i.e., the engine, transmission, and final drive).

It is pointed out in Appendix K that a major feature of land vehicles is that the thruster is also the lift device, whereas in air and sea vehicles these functions are generally separated.* The lifting function of land thrusters dominates their design, with the result that their weight is a function of the gross vehicle weight (GVW) rather than of thrust power. Data presented in Appendix K shows that the weight of tracks or wheels (including their suspension) can be taken as a fixed fraction of GVW for each vehicle class, independent of the thrust power required. On the other hand, the rest of the propulsion system is sized primarily by thrust power requirements. The weight and volume of the thrusters for LCVs are thus designated

*An exception is the helicopter.

W_{psw} and ∇_{psw}; for the rest of the system the designations are W_{psp} and ∇_{psp}.*

Using this approach and notation, a modified form of Eq. II-1 can be developed for LCVs (see Appendix A, Eq. A-11, p. A-8):

$$SFC\left[\frac{(HP\text{-}HRs)_{cr}}{W_v}\left(1 + \alpha + \frac{\beta}{\rho_f}\right)\right] + SW_{psp}\left[\left(1 + \alpha + \frac{\beta}{\rho_{psp}}\right)\right]\frac{P_{max}}{W_v}$$

$$= 1 - \frac{W_{psw}}{W_v} - \frac{W_L}{W_v}\left(1 + \alpha + \frac{\beta}{\rho_L}\right), \qquad \text{(II-2)}$$

where $\alpha(W_L + W_{psp} + W_F)$ = structural weight in hull

$\beta(\nabla_L + \nabla_{psp} + \nabla_F)$ = armor weight in hull

ρ_i = density of i^{th} element = W_i/∇_i.

Equation II-2 is plotted in Fig. II-3. When Fig. II-3 is compared to Fig. II-1, one sees that a major difference is that the location of the indifference line is now dependent on the armor protection and on the weight of the thruster, in addition to mobility, range, and payload-carrying specifications. It appears necessary, therefore, to treat LCVs in different classes, depending on whether they are lightly or heavily armored and on whether they use wheels or tracks as thrusters. The particular classes of LCVs selected for this study are

- Main battle tanks (MBTs)
- Light tracked combat vehicles (e.g., APCs)
- High-mobility combat vehicles (lightly armored, wheeled or tracked).

*The subscript psw indicates propulsion system--weight dependent, while the subscript psp indicates propulsion system--power dependent.

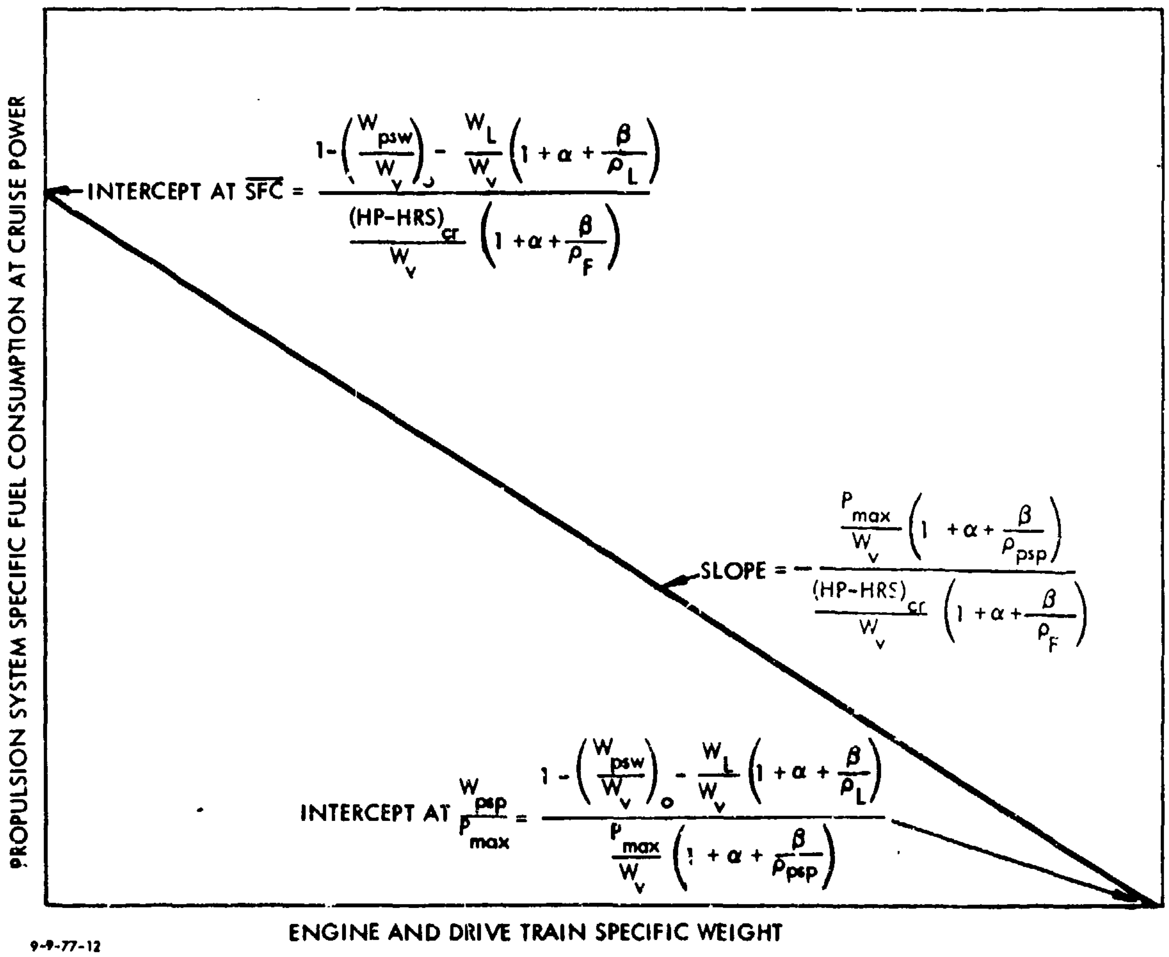

FIGURE II-3. Relationships between propulsion system parameters and LCV characteristics.

The remainder of this section considers the individual constraints that each of these classes of vehicles places on its propulsion system.

B. MAIN BATTLE TANKS (MBTs)

1. Vehicle Characteristics

The M-60 tank was used as a basic reference design for MBTs. This vehicle has gone through a number of improvements since it was first introduced into field operations. The specific configuration selected here is the M60A1 RISE, on which a great deal of performance and cost data is available. This information is used in Appendix A to derive the indifference line shown in Fig. II-4. The elationship of the installed system specific weight (29 lb/hp) and the system specific fuel consumption (0.61 lb/hp-hr) based on thrust power to the more familiar subsystem parameters and losses is shown in Table II-2.

In addition, results for advanced MBT designs were obtained by using, in the M-60 model calculations, engine parameters typical of later diesel and turbine tank engine developments. These are also shown in Fig. II-4. It is apparent that the newer propulsion systems represent a considerable improvement (better than a factor of two) in system specific weight when compared to the M-60. It also appears that even though the turbine and diesel systems have quite different weight and specific fuel consumption characteristics (the turbine being lighter but less efficient), they fall very nearly on the same indifference line and so appear equally acceptable for this application.

For the purposes of this study, we take the advanced MBTs defined in this way as rational vehicles representing the current state of the art in MBTs. The question to be addressed first in this section is what further improvements in propulsion system parameters would be needed to make a major impact on MBTs

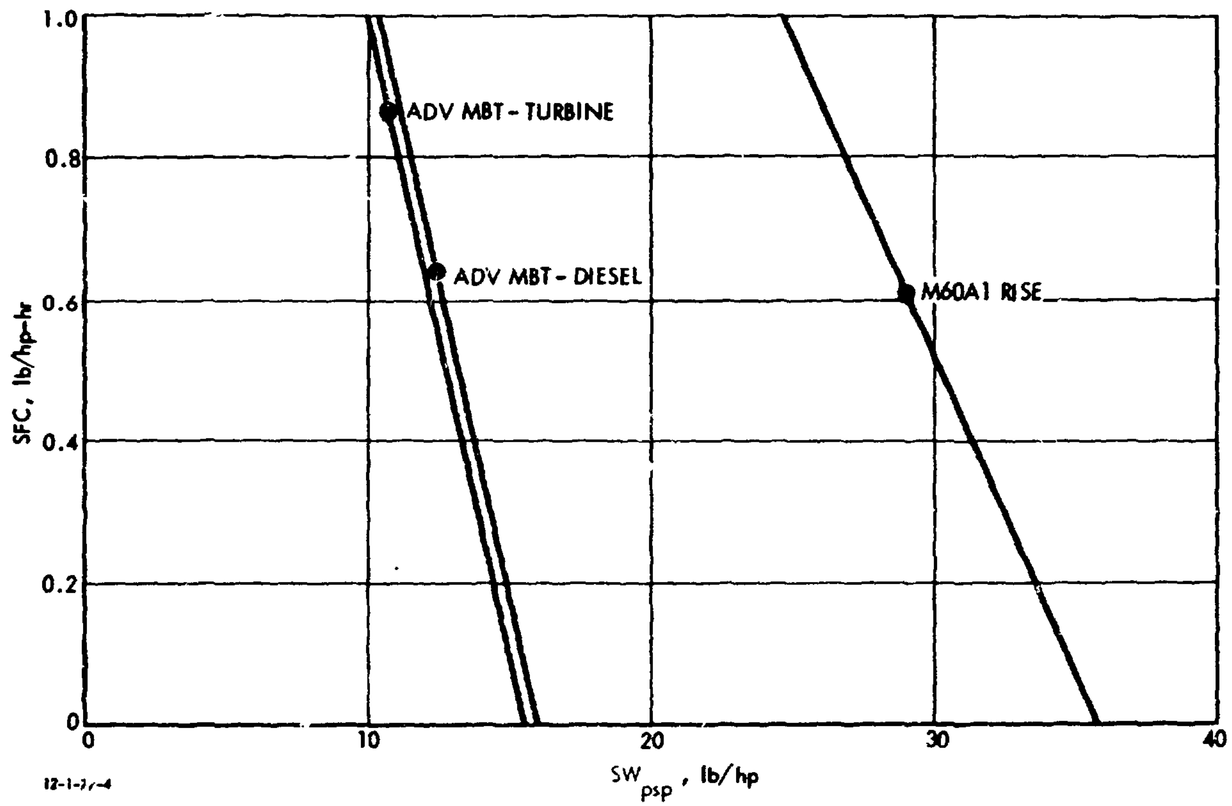

FIGURE II-4. Indifference lines for main battle tanks.

as a class of vehicle. Then the question becomes what combinations of engine and transmission among those analyzed in this report have the potential for providing the required improvements.

TABLE II-2. PROPULSION SYSTEM PARAMETERS RELATED TO SUBSYSTEM CHARACTERISTICS FOR THE M-60 TANK

Reference Conditions	Specific Weight, lb/hp: Engine	Specific Weight, lb/hp: Transmission*	Specific Fuel Consumption, lb/hp-hr
Bare engine, gross power	7.0		0.38
Installed weights	8.9 (gross power)	10.5 (input power)	
Corrected for:			
- Cooling power	10.0	10.8	0.44
- Transmission efficiency	12.7	13.7	0.56
- Thruster efficiency	14.0	15.0	0.61
Installed system, thrust power	29.0		0.61

*Includes final drive.

2. Cost Sensitivity Factors

It is common to assess the impact of improved technology in one of the systems that compose a vehicle by calculating the effect on some vehicle characteristic (size, speed, range, payload) of a change in the system characteristics. Such sensitivity factors are calculated in Appendix A in terms of both weight and cost impact on the vehicle. As noted above, we choose here to measure the benefit of a system change in terms of its impact on the cost of the vehicle if its performance (including payload-carrying ability) is not changed. Thus, the cost sensitivity

factor is defined as the fractional change in cost (at fixed performance) due to a fractional change in the system parameter, e.g.,

$$\frac{\Delta \$_T}{\$_T} = SC_i \frac{\Delta Q_i}{Q_i} \quad ,$$

where SC_i = cost sensitivity factor

$\Delta\$_T/\$_T$ = fractional change in vehicle platform costs (i.e., without payload costs)

$\Delta Q_i/Q_i$ = fractional change in propulsion system parameter.

The cost sensitivity factors for the advanced MBTs shown in Fig. II-4 are given in Table II-3.

These factors are of interest in that they measure the relative impact of equal fractional changes in the parameters. Thus it can be seen that a given change in the power-train specific weight, SW_{psp}, has more impact than the same fractional change in specific volume, SV_{psp}.* It is also seen that the impact of a change in the thruster specific weight, SW_{psw}, has as large an impact as an equal change in power-train weight and volume combined. Other such qualitative comparisons can be made. It is convenient here to make the comparisons more quantitative and to show them graphically.

*This results from the high density of the power train. For the payload, which has much lower density, the volume has more impact than weight.

TABLE II-3. COST SENSITIVITY FACTORS FOR MBTs

Parameter	Cost Sensitivity Factor M-60	Advanced (Diesel)	Advanced (Turbine)
Propulsion Power System Specific Weight, SW_{psp}	0.360	0.318	0.268
Propulsion Power System Specific Volume, SV_{psp}	0.213	0.173	0.138
Propulsion Support System Specific Weight, SW_{psw}	0.497	0.468	0.458
Specific Fuel Consumption, SFC	0.144	0.173	0.138
Fuel Density, ρ_F	-0.058	-0.066	-0.087
Propulsion System Procurement Cost (Power), $\$_{pp}$	0.121	0.166	0.164
Propulsion System Maintenance Cost (Power), $\$_{mp}$	0.243	0.331	0.329
Fuel Cost, $\$_F$	0.026	0.037	0.050

3. Goals for a Major Advance

To set quantitative goals, a major advance is defined as a combination of improvements that would give a 20-25% change in vehicle cost per unit payload at fixed performance. If this impact is to be derived from a combined change in specific fuel consumption and power-train specific weight and volume (at constant density), the new system must match some point on the shaded areas shown in Fig. II-5. These areas may, therefore, be regarded as providing parametric goals for a major advance in MBT power-train systems, in the same sense that the advanced MBT systems represent a major advance over the M-60.

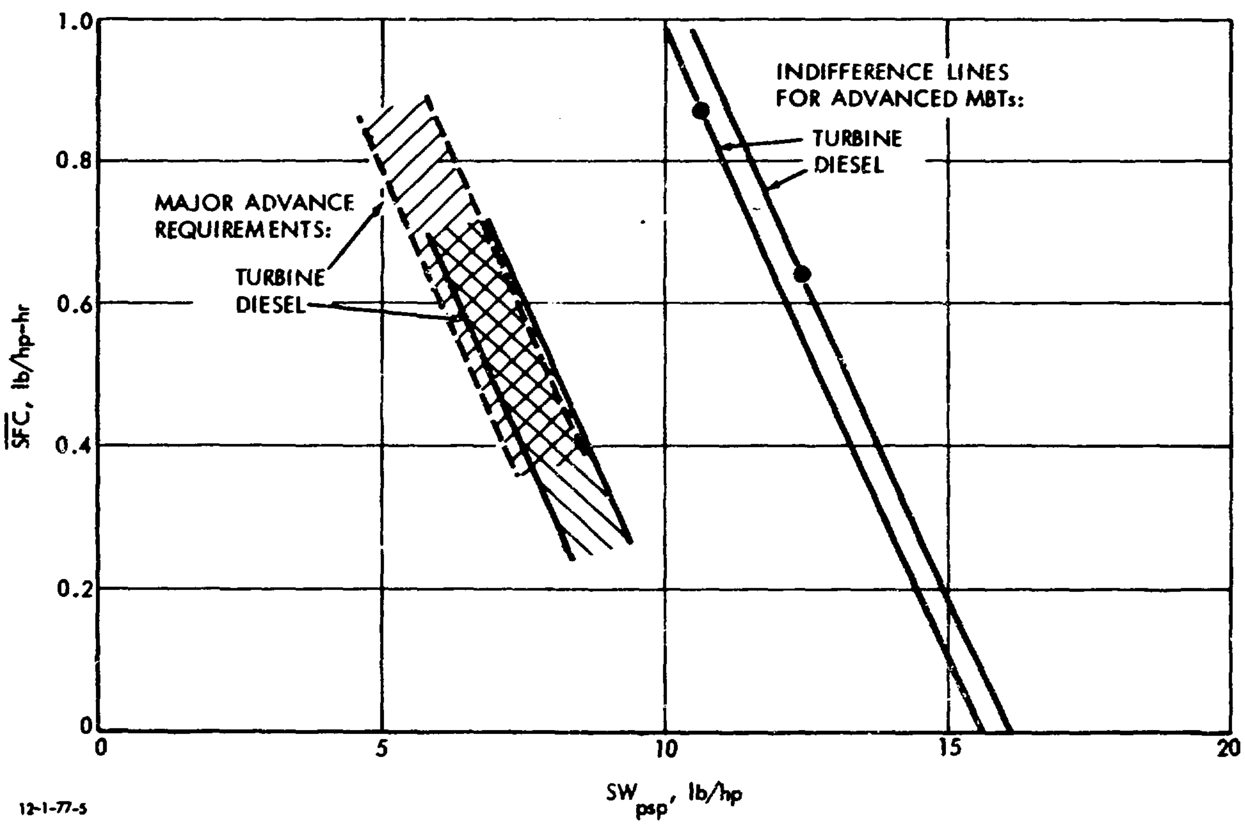

FIGURE II-5. Propulsion system goals for a major advance in MBTs.

A major impact, as defined here, could also be obtained by other improvements in the propulsion system such as a factor-of-two improvement in the support-system specific weight, or in the combined specific procurement and maintenance costs (i.e., costs per unit of power). In general, these can be treated independently of the goals shown in Fig. II-5 for the purpose of this analysis. The propulsion system cost sensitivities can be used to evaluate the importance of costs relative to performance advances. For example, if reaching the goals shown in Fig. II-5 caused a 50% increase in the power-train specific costs, there would be about a 25% increase in cost per unit payload (Table II-3. This impact is as large as that of reaching the performance goals, and thus maintaining specific costs at historic levels is important in this application. The fuel density and fuel cost sensitivities are shown in Table II-3 for interest but do not affect these considerations in any significant way.

C. TWO OTHER CLASSES OF LCVs

The indifference lines and the cost sensitivity factors for two other classes of LCVs are calculated in Appendix A. The two classes are (1) the light tracked LCV, for which we will use the M113 armored personnel carrier and the M551 light tank as the reference designs, and (2) the high-mobility LCV, for which we will use the XM808 as the reference design. The indifference lines for these vehicles are shown in Fig. II-6, and the cost sensitivity factors in Table II-4. As before, the major advance criterion can be used to establish a new indifference line that sets goals for an improved power-train system. These are shown also in Fig. II-6.

The sensitivity factors show that, compared to the MBT, the impact of power-train volume is reduced in the light tracked LCV due to the lighter armor. As a result, the combined specific weight and volume sensitivities for the power train are lower than for the MBT. It is interesting to note also that the other

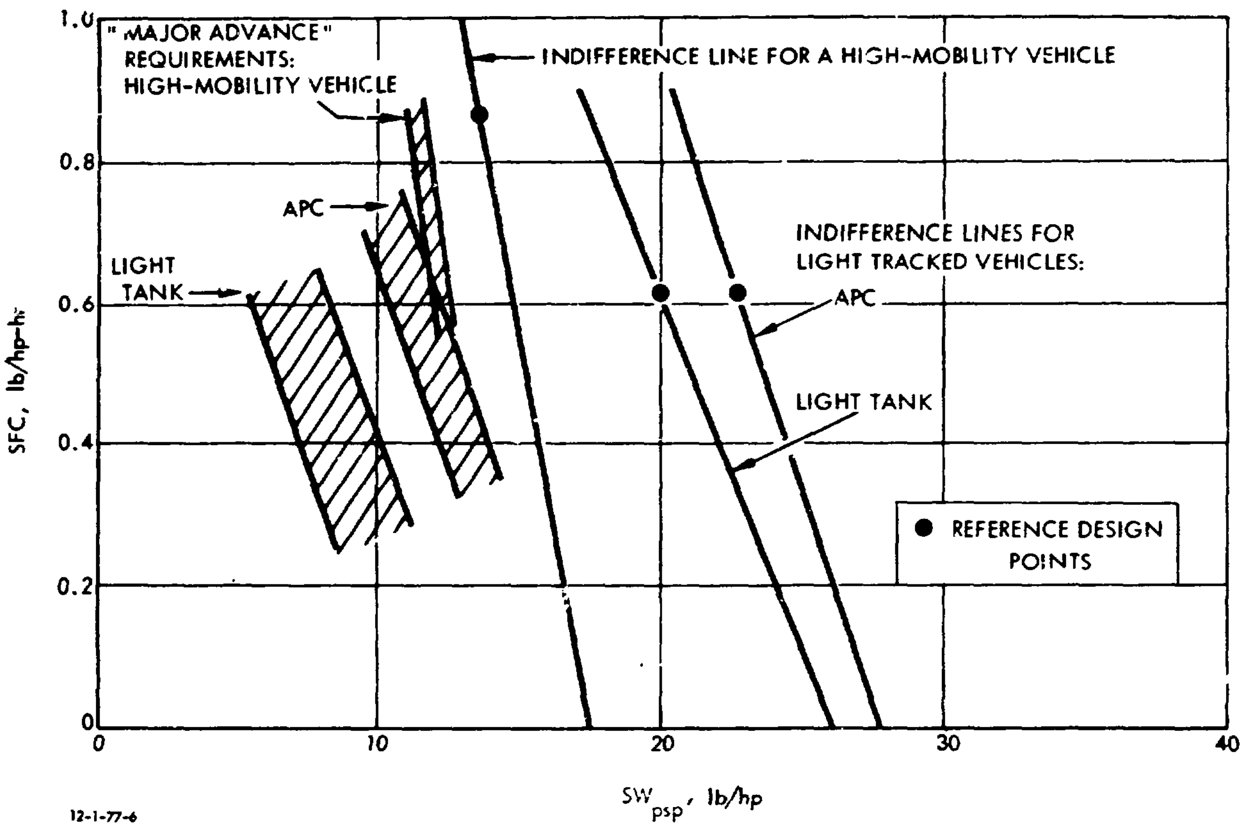

FIGURE II-6. Indifference lines for light tracked LCVs and high-mobility LCVs and major advance goals.

parameters of interest, i.e., the specific weight of the support system and the procurement and maintenance costs, have nearly the same sensitivity in the light tracked LCV and the MBT.

TABLE II-4. COST SENSITIVITY FACTORS FOR TWO CLASSES OF LAND COMBAT VEHICLES

Parameter	Light Tracked LCV: Tank (Diesel)	Light Tracked LCV: APC (Diesel)	High-Mobility LCV: Articulated Wheeled (Gasoline)
Propulsion Power System Specific Weight, SW_{psp}	0.282	0.383	1.090
Propulsion Power System Specific Volume, SV_{psp}	0.047	0.075	0.128
Propulsion Support System Specific Weight, SW_{psw}	0.422	0.475	0.842
Specific Fuel Consumption, SFC	0.110	0.118	0.290
Fuel Density, ρ_F	-0.018	-0.019	-0.036
Propulsion System Procurement Cost (Power), $\$_{ps}$	0.146	0.149	0.191
Propulsion System Maintenance Cost (Power), $\$_{mp}$	0.292	0.299	0.383
Fuel Cost, $\$_F$	0.031	0.032	0.059

The M551 uses somewhat later propulsion system technology than the M113, which accounts for its different position in Fig. II-6. There is in development an up-powered M113 that also uses later technology and shifts the M113 line close to the M551. For this reason we take the M551 as a rational vehicle representative of light tracked LCVs, and use it to establish the major advance goals for this class of vehicles, shown by the shaded area for light tanks in Fig. II-6.

In the high-mobility vehicle there is a considerable increase in the propulsion system weight and volume sensitivities (see Table II-4), which reflects an increased fraction of the vehicle devoted to propulsion system and a reduced fraction devoted to payload. To get greatest power for least weight, gasoline engines and wheels were used in the propulsion system. The result is a vehicle with high specific power (the hp/ton is about three times as great as the M113--an equivalently sized vehicle).

Because of the large propulsion system and small payload (half the M113 payload) in this vehicle, the change in propulsion system parameters needed to make a major impact is relatively small. This is shown graphically in Fig. II-6, where it is seen that greater improvements in the propulsion system are needed to have a major impact on the M551 or the M113 than on the XM808. The fallacy here arises from using an experimental vehicle as a reference design, i.e., in the terms used here it has not been proven to be cost-effective and is not a "rational" vehicle. As a practical field vehicle with heavier armor and more payload, the XM808 would come more nearly into line with the M551 and the up-powered M113.

It appears, then, that it is not necessary to establish major advance goals for high-mobility vehicles, independent of other medium-size vehicles. If an improved propulsion system meeting the major advance goals for the M551 or the up-powered M113 is obtained, it can be used to provide greater mobility if the other vehicle specifications are held constant (e.g., for equal payload, armor, and range the advanced MBTs considered above have twice the hp/ton of the M-60).

D. HIGH-SPEED OCEANGOING SHIPS

1. Vehicle Characteristics

In Appendix B these same methods are used to analyze the propulsion system needs of high-speed (over 50 knots) oceangoing

(4000 nmi range) ships. The major differences from the LCV analysis are, first, that this class of ships can be treated as primarily weight-sensitive, which simplifies the vehicle analysis, and, second, that all elements of the propulsion system, including the thruster, are power dependent, which complicates the propulsion system analysis by providing additional possible weight and efficiency tradeoffs between the transmission and the thruster.

The results of the vehicle analysis are shown in Fig. II-7 for the most attractive candidate, a surface-effect ship (SES) with length-to-beam ratio of 6.5. In comparing this figure to the similar figures for LCVs given above, it should be noted that the percentage of shaft power delivered as cruise thrust power is typically about 50% in a high-speed ship, compared to about 70% in an LCV. Therefore, the attainable system specific fuel consumption (SFC) is typically higher in a ship than in an LCV. The specific weight axis is similarly distorted. The significant comparison between the SES and the LCV indifference lines is in the great difference in slope, which reflects the much greater range requirement in the SES. The fuel weight in the SES is by far the greater part of the total propulsion system, which is the inverse of the situation in the LCVs. This reduced slope of the indifference line for the SES puts a far greater emphasis on improved SFC than in the LCV case.

2. Propulsion System Goals

The calculations done in Appendix B assume a propulsion system weight fraction of 0.5, i.e., one-half the total vehicle weight is devoted to propulsion system. As pointed out in Appendix B (p. B-12), for escort ships actually in service, the propulsion system weight fraction is between 0.25 and 0.35. Again, as with the high-mobility LCV, there is no high-speed ship in existence which meets our rational vehicle definition. For the purposes of setting goals for a major advance, it is

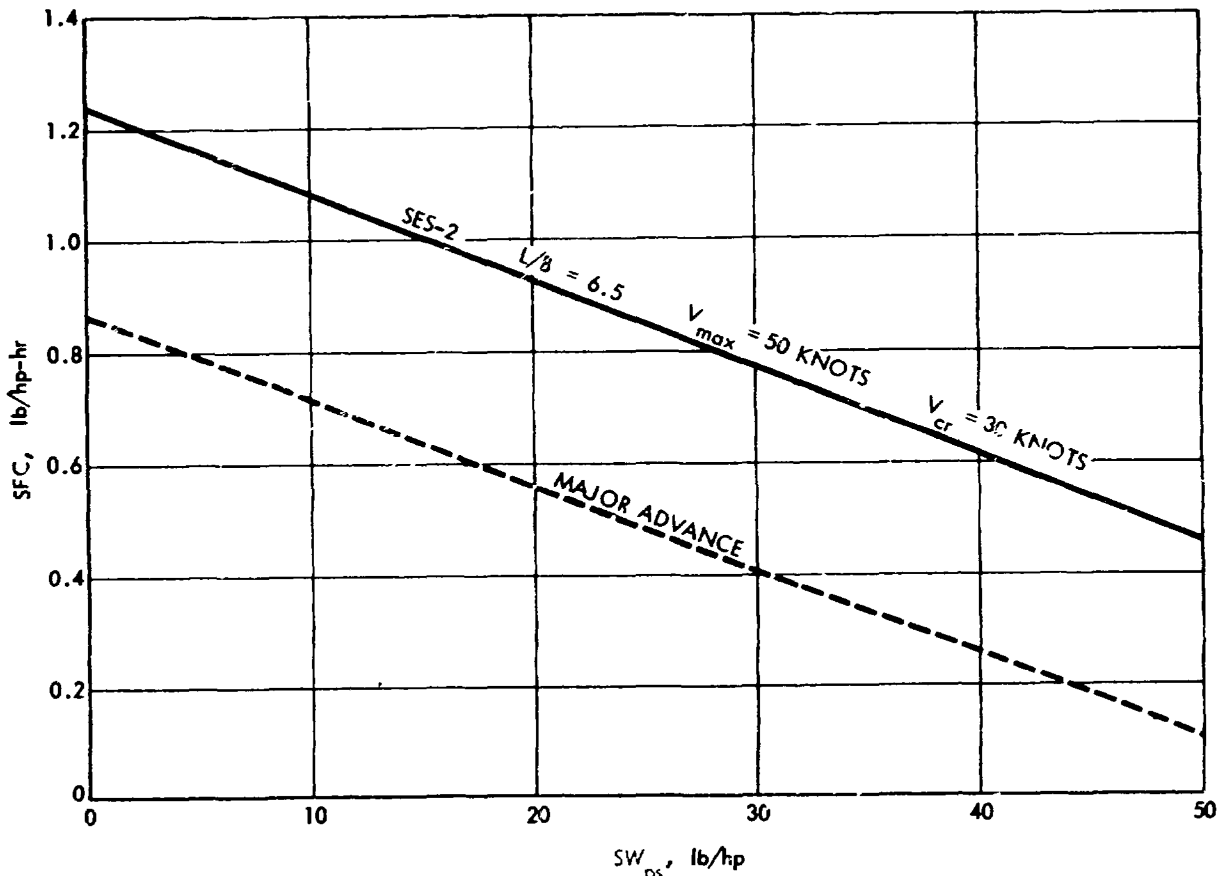

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FIGURE II-7. Propulsion system goals for high-speed oceangoing ships.

assumed here that the maximum permissible value of W_{ps}/W is 0.35 as it is in service-proven escort vessels which do meet the criteria for rational vehicles. The effect of this change is to scale each axis by the ratio 0.35/0.50 (as can be seen from Fig. II-1), which gives the line marked "major advance" in Fig. II-7. The cost sensitivity factors associated with a vehicle designed on this line with propulsion system parameters SFC = 0.7 lb/hp-hr and SW_{ps} = 10.1 lb/hp are given in Table II-5. These were derived from the vehicle characteristics presented in Appendix B and the cost formulation given in the article referenced in the Introduction.*

TABLE II-5. COST SENSITIVITY FACTORS FOR A HIGH-SPEED SHIP

Parameter	Cost Sensitivity Factor
SW_{ps}	0.25
SFC	1.20
$\$_{ps}$	0.06
$\$_F$	0.05

E. SUITABLE GOALS AND RELATIVE PAYOFFS FOR LAND COMBAT VEHICLES

It will be seen from the above that the SFC and SW_{ps} values required for a major advance in both MBTs and light LCVs (i.e., M551 values) are essentially the same, and hence can be used for all LCVs. The differences between classes are (1) in the power level at which the SFC/SW_{ps} values are to be achieved (i.e., 1000-1500 hp for MBTs and 300-800 hp for light LCVs) and (2) in the relative payoffs (as evidenced by the differences in cost sensitivity factors between classes).

*D.M. Dix and F.R. Riddell, "Projecting Cost-Performance Trade-offs for Military Vehicles," *Aeronautics and Astronautics*, September 1976.

1. Suitable Technology Goals for LCVs

The informatic eveloped above for LCVs is plotted together with selected pr ›n ›ion system characteristics from Section .II in Fig. II-8. The only propulsion systems of the ones studied that had potential limits which exceeded the demands for a major advance are the diesel- and turbine-powered systems with hydrodynamic transmissions that are shown.* It is seen that the current-technology diesel system results agree quite well with the advanced MBT vehicle calculations. That is to say, the diesel-powered propulsion system characteristics are tangent to the vehicle indifference line r .ar the design point (as discussed above, Fig. II-2). The turbine-powered system, however, crosses the indifference line. The implication of this is that there is current technology that could produce a lighter or more efficient turbine propulsion system than was assumed in the advanced MBT vehicle calculations (i.e., the AGT 1500 turbine with the XM1100 transmission). The basic difference appears to be that the current technology assessment gives a regenerated turbine like the AGT 1500 better efficiency than it actually shows. If we considered the AGT 1500 to be on an earlier technology line, . .e curve would shift up and to the right and be more nearly tangent to the indifference line.

Comparison of the potential limits and the major advance requ.rements for each system allows selection of an advanced vehicle design point around which a cross-hatched area is drawn in Fig. II-8 to indicate technology goals for a major advance. Because of the different characteristics of the two systems the technology goals fall in different areas. Note that the range of values selected as goals is constrained by the "potential limit" lines for each system. Goals defined in this way are termed "suitable goals" in this report.

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*It is assumed that mechanical transmissions are not acceptable on other grounds.

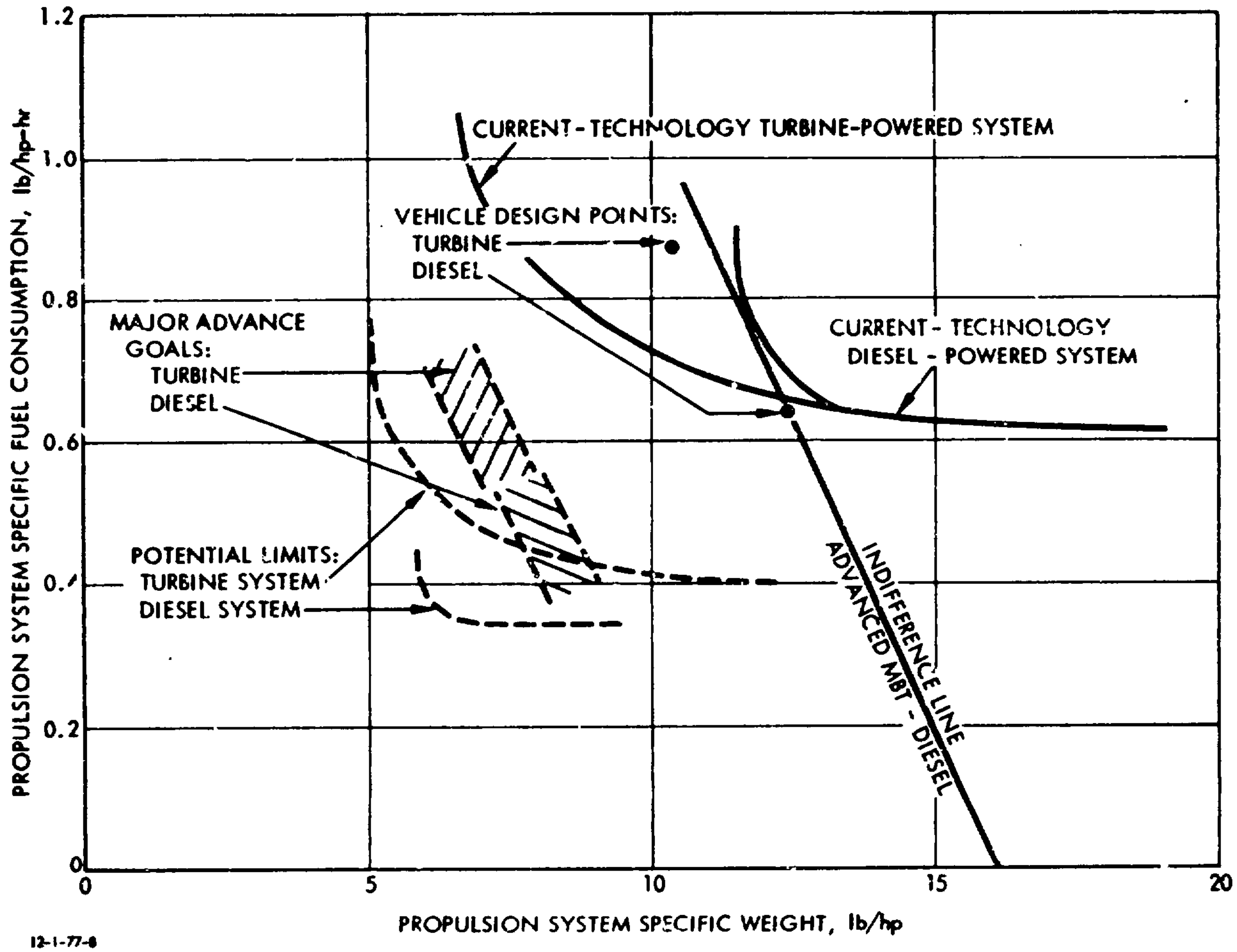

FIGURE II-8. Propulsion system goals for LCVs.

2. Relative Payoffs

As noted above, relative payoffs are established by computing how much each characteristic contributes to the total impact (i.e., a 20-25% cost reduction). This is done using the cost sensitivity factor and the incremental change for each characteristic to reach the goal values. The results are thus seen to depend on the specific application. For MBTs the results are given in the following table.

Propulsion System Type	System Parameter	Current Value	Suitable Goals	Relative Payoff
Diesel System	SFC	0.64	0.45	0.05
	SW	12.4	7.9	0.12
	SV	0.16	0.10	0.06
Turbine System	SFC	0.87	0.66	0.06
	SW	10.7	6.2	0.11
	SV	0.13	0.063	0.06

Note that in each case the sum of the relative payoffs is 0.23, which is the total cost impact. In both systems reductions in SW have the greatest relative payoff. If it is assumed that system density remains constant, the SW and SV impacts are additive and size reduction is clearly dominant over SFC reduction. For light LCVs the results are similar except that the impact of SV is reduced because of the lighter armor. Between systems it is seen that SFC reduction is slightly more important in the turbine system than in the diesel system. These relative payoff results are fairly obvious at the system level but less so at the subsystem level which is discussed in the next section.

F. SUITABLE GOALS AND RELATIVE PAYOFFS FOR A HIGH-SPEED SHIP

1. Suitable Technology Goals

In Fig. II-9 vehicle characteristics developed above and propulsion system characteristics (from Section III) are plotted

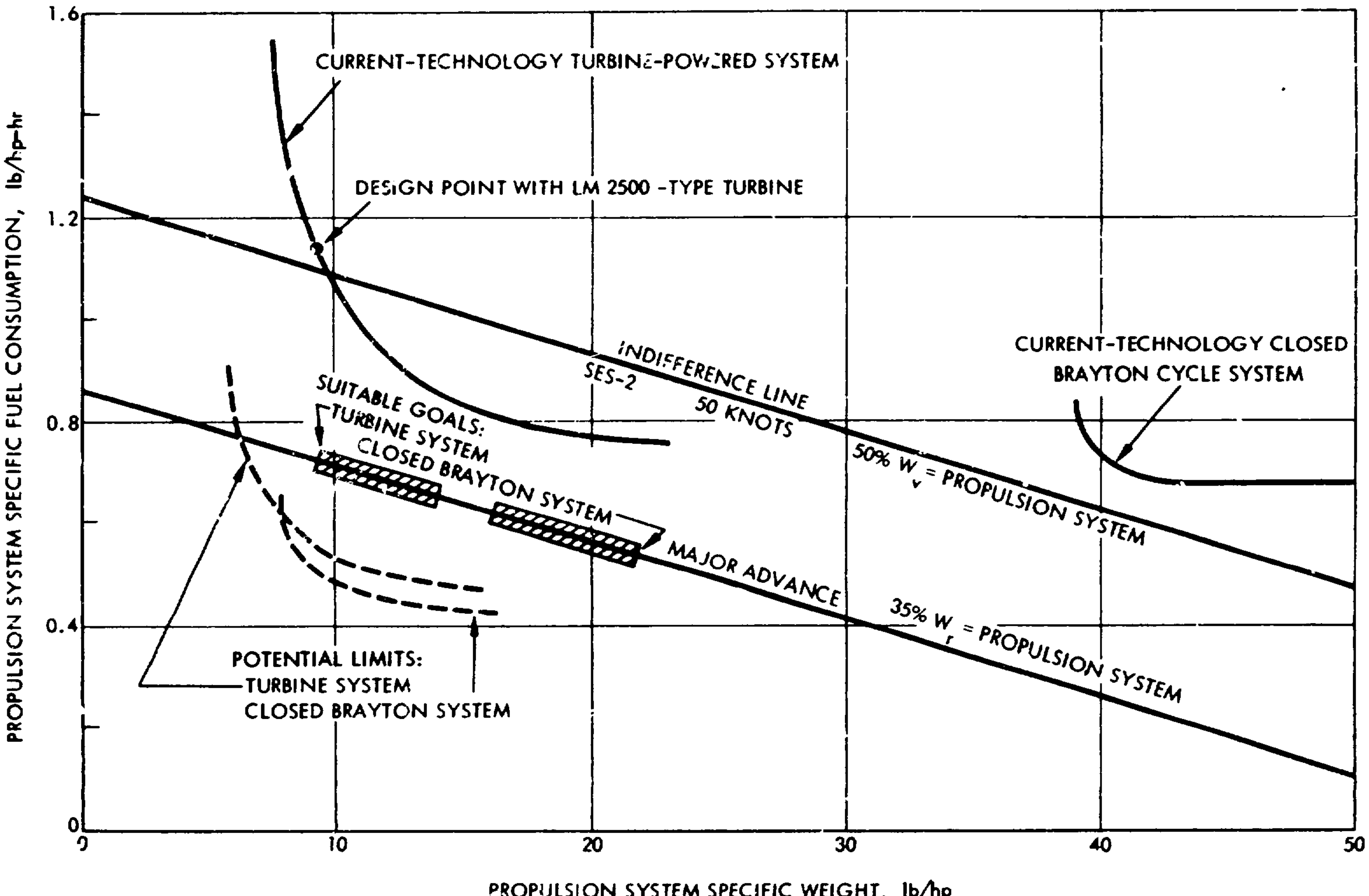

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FIGURE II-9. Propulsion system goals for high-speed ships.

for a high-speed ship. In this case the only two systems of the ones analyzed that had appropriate characteristics for this application were found to be a turbine-waterjet system and a closed Brayton-cycle-waterjet system, which are shown. Considering the turbine system, first note that a design point is shown using the open-cycle turbine like the LM 2500. This is nearly on the indifference line for an SES of 50-knot speed with one-half its weight devoted to propulsion, which are typical design-study vehicle characteristics. It is interesting to note that this design point is not at a tangent point with the indifference line. The indication here is that a much bigger, heavily regenerated turbine consistent with the lower SFC values would more than pay for its additional size. Also shown in Fig. II-9 is a current-technology curve for a closed Brayton system, consisting of a closed Brayton engine and the same mechanical transmission and waterjet technology as used in the turbine system. It appears that with current technology the far greater weight of this system does not pay for its greater efficiency in this application, since it falls above the indifference line.

Potential limits for the system characteristics are also shown for both systems by the dashed lines in Fig. II-9. As before, these are developed in Section III based on estimates of what may be physically possible in improving subsystem performances. It is seen that the two systems become competitive in this projection, and indeed would make it possible to reduce propulsion system weight fraction to levels consistent with past practice (i.e., less than 0.35).

Suitable technology goals are also indicated by the cross-hatched areas for each propulsion system. The spread across the major advance line indicates a 5% spread in cost impact as was used for the LCV case.

2. Relative Payoffs

For the SES, relative payoffs are as shown in the following table. It should be noted that in this case the relative payoffs do not sum to 0.23 because of the different criterion used to define a major advance. Also, specific volume has little impact in this application, so only SW and SFC are shown.

Propulsion System Type	System Parameter	Current Value	Suitable Goals	Relative Payoff
Turbine-	SFC	1.15	0.66	0.55
Waterjet	SW	9.5	10.6	(0.02)
Closed Brayton-	SFC	0.71	0.55	0.18
Waterjet	SW	40.2	18.9	0.35

The relative payoffs are seen to be quite different for the two different types of propulsion systems: specific fuel consumption reduction has by far the most impact in the gas-turbine system, while specific weight reduction is the more important in the closed Brayton-cycle system. These differences are of course due to the basic differences in the current engines: gas turbines are relatively light and inefficient compared to closed Brayton-cycle engines, a fact which is also indicated by the relative goals.

It is also interesting to note that an *increase* in SW for the turbine system is indicated compared to the current design point. This indicates that for this application at the new design point the payoff in reduced SFC more than compensates for the increased system weight necessary to attain the reduced SFC. The subsystem characteristics that give rise to this result are discussed in the next section.

III. SUBSYSTEM IMPACTS ON PROPULSION SYSTEMS FOR SELECTED VEHICLE CLASSES

In the previous section, suitable goals and their relative payoffs were established for propulsion systems, on the basis that such goals would achieve a major impact on the vehicle classes considered. In order that such goals and payoffs be useful in providing guidance for the individual subsystems--engine, transmission, thruster--it is necessary to develop from them the corresponding suitable goals and relative payoffs for each individual subsystem. This development is the primary objective of this section.

It will be recalled that the system goals are based upon estimates of the current state-of-the-art characteristics and potential limits of propulsion systems, which of course depend upon both the corresponding estimates of subsystem characteristics (which will be developed in Section IV) and the interactions which occur among the individual subsystems. Thus, a second objective of this section is to develop system characteristics from subsystem characteristics in a way which appropriately considers the interactions among the subsystems.

The treatment of these interactions is largely a procedural question, but an understanding of the process facilitates an appreciation of the correspondence between subsystem goals and system goals. Thus, the procedures used in treating these interactions and the consequent determination of subsystem goals and payoffs are discussed in the first subsection. Subsequent subsections deal respectively with the subsystem characteristics actually used, an overview of the subsystem goals which result, and a more detailed discussion of the subsystem goals and payoffs which pertain to each vehicle class.

A. ANALYSIS OF SYSTEM-SUBSYSTEM INTERACTIONS

1. System-Subsystem Relationships

To develop system characteristics from subsystem characteristics, the basic need is to establish the correspondence between a point on a system characteristic and the corresponding subsystem points which produce it. The quantitative relationships which determine the five system characteristics of interest (specific weight, specific volume, specific fuel consumption, specific procurement cost, and specific maintenance costs), given corresponding values for the subsystem characteristics, are virtually trivial; for the record, they are indicated in Fig. III-1 with the associated notation. The interactions which occur among the subsystems are not so trivial, however; these interactions are depicted schematically in Fig. III-2, for the simple case where only the interactions concerning specific fuel consumption and specific weight are considered.

The interactions depicted in Fig. III-2 originate from the fact that in power conversion machinery it is usually possible to trade off better efficiency for greater specific weight (and conversely) by design changes, without changing the state of technology. Typically, then, the relationships between efficiency and specific weight of the individual subsystems, for a given state of technology, are as shown in the upper part of Fig. III-2. Since any point on a subsystem curve represents a possible design point for the subsystem, and since a subsystem design point is in principle independent of the design points of the other subsystems, then the straightforward combination of the subsystem characteristics will produce a family of system characteristics, as depicted in the lower part of Fig. III-2. However, the combinations of interest in this case are those that produce the minimum value of system SFC at any particular value of SW. The locus of these minimum values is the envelope of the values resulting from all possible combinations, and it is only such

γ_F, Fuel energy/lb → Engine → Transmission → Thruster → Thrust Power P_t

(a) Propulsion System Schematic.

Quantity	Engine	Transmission	Thruster	Total System
Weight	W_e	W_x	W_t	W_{ps}
Volume	∇_e	∇_x	∇_t	∇_{ps}
Efficiency	$\eta_e \sim (sfc)^{-1}$	η_x	η_t	$\eta_{ps} \sim (SFC)^{-1}$
Power Out	P_e	P_x	P_t	P_t
Specific Weight	$sw_e = \frac{W_e}{P_e}$	$sw_x = \frac{W_x}{P_x}$	$sw_t = \frac{W_t}{P_t}$	$SW_{ps} = \frac{W_v}{P_t}$
Specific Volume	$sv_e = \frac{\nabla_e}{P_e}$	$sv_x = \frac{\nabla_x}{P_x}$	$sv_t = \frac{\nabla_t}{P_t}$	$SV_{ps} = \frac{\nabla_v}{P_t}$
Specific Fuel Consumption	sfc_e			SFC_{ps}
Specific Procurement Cost	$\left(\frac{\$_e}{P_e}\right)$	$\left(\frac{\$_x}{P_x}\right)$	$\left(\frac{\$_t}{P_t}\right)$	$\frac{\$_{PP}}{P_t}$
Specific Maintenance Cost	$k\left(\frac{\$_e}{P_e}\right)$	$k\left(\frac{\$_x}{P_x}\right)$	$k\left(\frac{\$_t}{P_t}\right)$	$\frac{\$_{MP}}{P_t}$

(b) System and Subsystem Notation.

$$SW_{ps} = \frac{sw_e}{\eta_x \eta_t} + \frac{sw_x}{\eta_t} + sw_t$$

$$SV_{ps} = \frac{sv_e}{\eta_x \eta_x} + \frac{sv_x}{\eta_t} + sv_t$$

$$SFC_{ps} = \frac{1}{\gamma_F \eta_e \eta_x \eta_t} = \frac{sfc_e}{\eta_x \eta_t}$$

$$\frac{\$_{PP}}{P_t} = \left(\frac{\$_e}{P_e}\right)\frac{1}{\eta_x \eta_t} + \left(\frac{\$_x}{P_x}\right)\frac{1}{\eta_t} + \left(\frac{\$_t}{P_t}\right)$$

$$\frac{\$_{MP}}{P_t} = k\left(\frac{\$_{PP}}{P_t}\right)$$

(c) System-Subsystem Relationships.

FIGURE III-1. System-subsystem schematic, notation, and relationships.

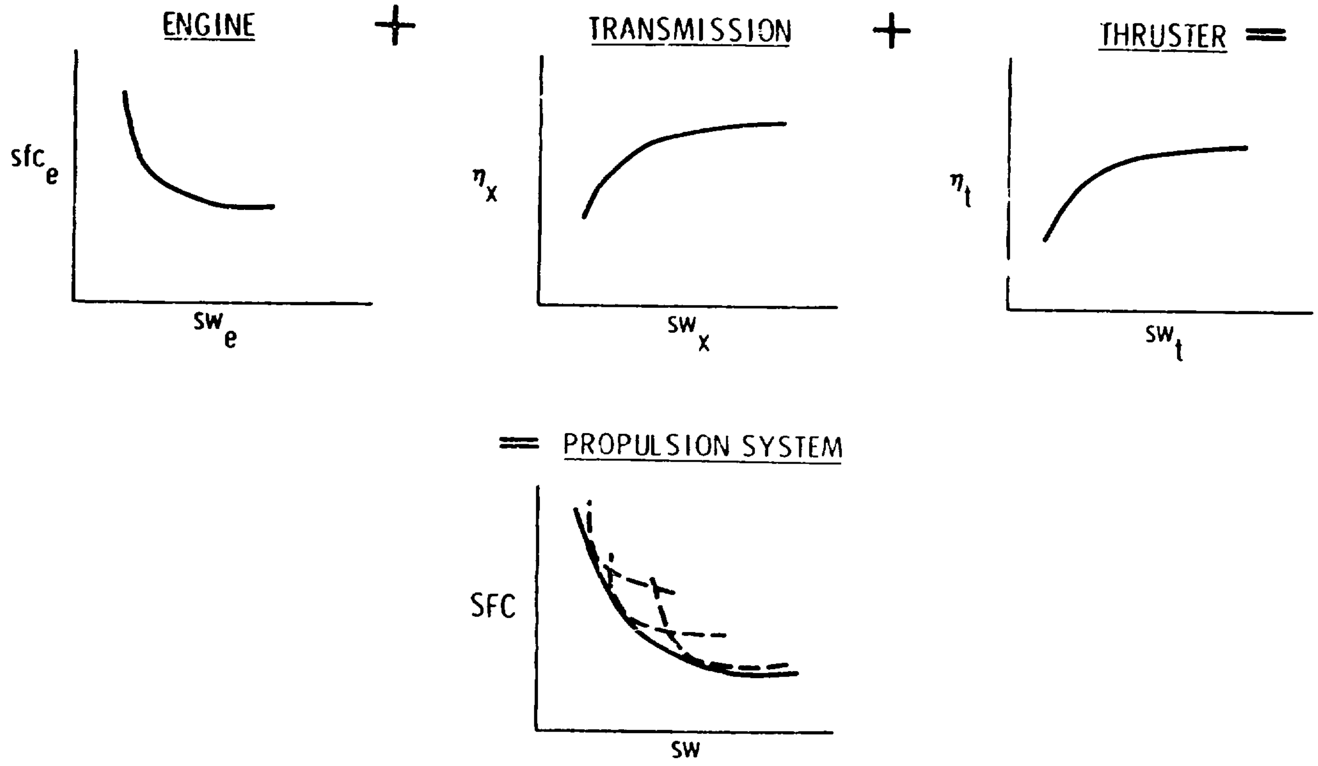

FIGURE III-2. Propulsion subsystem-system interactions.

envelopes that are of interest here as propulsion system characteristics.

The propulsion system characteristics presented in Section II were in fact developed in the above manner; that is, for any set of subsystems constituting a given type of propulsion system, the state-of-the-art characteristics or the potential limits were combined (by a computerized trial-and-error procedure using the equations in Fig. III-1) to produce the minimum attainable value of SFC over the appropriate range of specific weight. This produces a system SFC-SW characteristic either for the current state of the art or for the estimated limit, with values of specific volume and specific costs associated with each point on this envelope. It also identifies the corresponding subsystem points for each point on the envelope.

There are of course some approximations involved in this procedure. Obviously, one could equally produce a system SFC-SW characteristic which has the property that at every specific weight the SFC is the minimum attainable at the associated specific volume. Such an SFC-SW characteristic would be different than the one used here, and would result in a slightly different impact on the vehicle, depending upon the relative sensitivities of the vehicle to propulsion system specific weight and specific volume. Fortunately, the specific weight and the specific volume of propulsion systems tend to be generally related, and in addition, the specific weight tends to have the greater impact on the vehicles studied here (less on the main battle tank than the others), with the result that minimizing SFC at a given SW gives an adequate representation of the propulsion system.

Further, the efficiency-specific weight characteristic of a subsystem also depends, in general, upon both the power level and the shaft speed at which the power level is transmitted. For a given application, however, power level is confined to a rather narrow range. Thus, for practical purposes, the influence of

power level on subsystem characteristics can be neglected for a given vehicle application. Neither is there a great deal of flexibility in selecting shaft speed. For engines, the output speed at maximum power is closely tied to the power level for each type of engine, though it may vary considerably between types (e.g., turbines versus diesels). Thus the sfc-sw curves for engines are not significantly influenced by output speed variations within a given power range. For transmissions, the output speed is set by the thruster requirements. For LCVs, maximum power must be delivered for climbing slopes at low shaft speeds, which is set by the track or wheel design. Output speed is thus practically fixed in the propulsion system design. In high-speed ships, however, thruster speed is a variable which must be considered in optimizing weight. For supercavitating propellers, for example, as the shaft speed is reduced the efficiency increases, but so does the weight of both the propeller and the transmission (since a greater reduction ratio is required). In determining propulsion system characteristics for the high-speed ship, the characteristics of the transmission/thruster combination were calculated first and then combined with suitable engines.

2. Subsystem Goals and Payoffs

Since by definition the goals for propulsion systems established in Section II lie between current state-of-the-art characteristics and their estimated potential limits, it is equally true that the corresponding goals for constituent subsystems will lie between current state-of-the-art subsystem characteristics and their estimated potential limits. It is also evident that for any set of system goals, there are numerous possible sets of corresponding subsystem goals which will provide the desired system values. The only difference between such sets of subsystem goals is a varying proximity of individual subsystem characteristics to their estimated potential limits (for example, it may be possible to achieve the same system characteristics with an engine pushed to its potential limit and a state-of-the-art

transmission, or vice versa). The question is then how to establish reasonable goals for the individual subsystems.

It seems reasonable to define the subsystem goals so that all subsystem characteristics represent approximately equal fractional improvements of the difference between their current state-of-the-art values and their estimated potential limits, on the basis that these represent goals of approximately equal difficulty. Thus, for example, engine goals and transmission goals for a given propulsion system will represent approximately equal departures from their current state-of-the-art values toward their estimated potential limits. Inasmuch as the process of developing system characteristics from subsystem characteristics establishes (1) a point on each current state-of-the-art subsystem characteristic which corresponds to the current propulsion system design point, (2) a similar point on each subsystem potential-limit characteristic which corresponds to the potential limit of reduction in vehicle cost per unit payload, and (3) the magnitude of this reduction, subsystem goals representing equal fractional improvements can be obtained by straightforward interpolation.

As with propulsion system characteristics, sensitivity factors for the subsystems (i.e., the fractional change in a propulsion characteristic produced by a unit fractional change in a subsystem characteristic) can be determined by straightforward differentiation of the equations shown in Fig. III-1. Physically, such sensitivity factors merely reflect the relative importance of the various subsystem characteristics. For example, the subsystem sensitivity factor for engine specific weight will be high in a system in which the engine weight is dominant, and conversely. Sensitivity factors can then be combined with the propulsion system sensitivity factors (i.e., the fractional change in vehicle cost per unit payload produced by a unit fractional change in a propulsion system characteristic) to produce cost sensitivity factors for the individual subsystem

characteristics (i.e., the fractional change in vehicle cost per unit payload produced by a unit fractional change in a subsystem characteristic). Such subsystem cost sensitivity factors indicate the leverage associated with the individual subsystem characteristics and can be combined with the subsystem goals to produce the relative payoffs associated with each.

Although these procedural matters may seem overly formal and tedious, they are necessitated by a simple fact which deserves emphasis: Subsystem goals and high-payoff areas can only be identified if the application is known. This is evident from subsystem characteristic curves shown in Fig. III-2. Without analysis of the application, the desired area on a new technology curve is not known. In fact, different applications may call for different goals for the same subsystem. An example of this, as will be seen shortly, is in different turbine engine goals for a main battle tank and for a high-speed ship. The main battle tank calls for a lightly regenerated engine in which small size is emphasized ahead of sfc. The high-speed ship (HSS), on the other hand, calls for a highly regenerated engine in which sfc is emphasized ahead of weight.

Similarly, since the relative importance of a single subsystem characteristic depends both upon the location of the subsystem on its characteristic curve and the corresponding locations of the other subsystems (all of which is reflected by the subsystem cost sensitivity factors), high-payoff areas in subsystems are dependent upon the application. Pursuing the example cited above, it will be seen that the potential impact of reduction of turbine engine specific weight is the dominant payoff in the main battle tank application and is of no significance at all in the high-speed ship application.

B. SUBSYSTEM CHARACTERISTICS

As discussed in Section II, the specific applications to be analyzed here are (1) MBTs with diesel or turbine engines, hydromechanical transmissions and tracks; (2) light LCVs with diesel or turbine engines, hydromechanical transmissions and tracks; and (3) high-speed oceangoing ships with turbine or closed-Brayton-cycle engines, mechanical transmissions and waterjets. Inasmuch as a starting point for developing subsystem goals is the characteristics of the relevant subsystems, it is appropriate to introduce them here (although they are developed in Section IV). These are shown for engines in Fig. III-3, in the form of specific fuel consumption versus specific weight; for hydrodynamic transmissions in Fig. III-4, in the form of efficiency versus specific weight; and for mechanical transmission/waterjet combinations in Fig. III-5, in the form of efficiency versus specific weight. Associated with each point on these curves is a value of specific volume and, for each subsystem, values of specific procurement and maintenance costs (these are not shown).

Some features of these characteristics deserve mention. First, both current state-of-the-art and potential-limit characteristics are shown. In the former, there are not, of course, a sufficient number of actual engines to develop these curves; hence they are, in some regions, estimates of what engines could be built with current technology. The potential-limit characteristics are, as usual, to be interpreted as possibilities rather than probabilities. Second, the characteristics shown for engines are applicable only to uninstalled subsystems. To be used in the analysis here, it is necessary to include the additional weight and volume required for installation in the vehicle. This is accomplished by the use of installation factors, which vary between 1.2 and 1.3 for the engines and vehicles studied here, as shown in Table III-1. Third, the efficiency characteristics are those applicable to the 25% power condition,

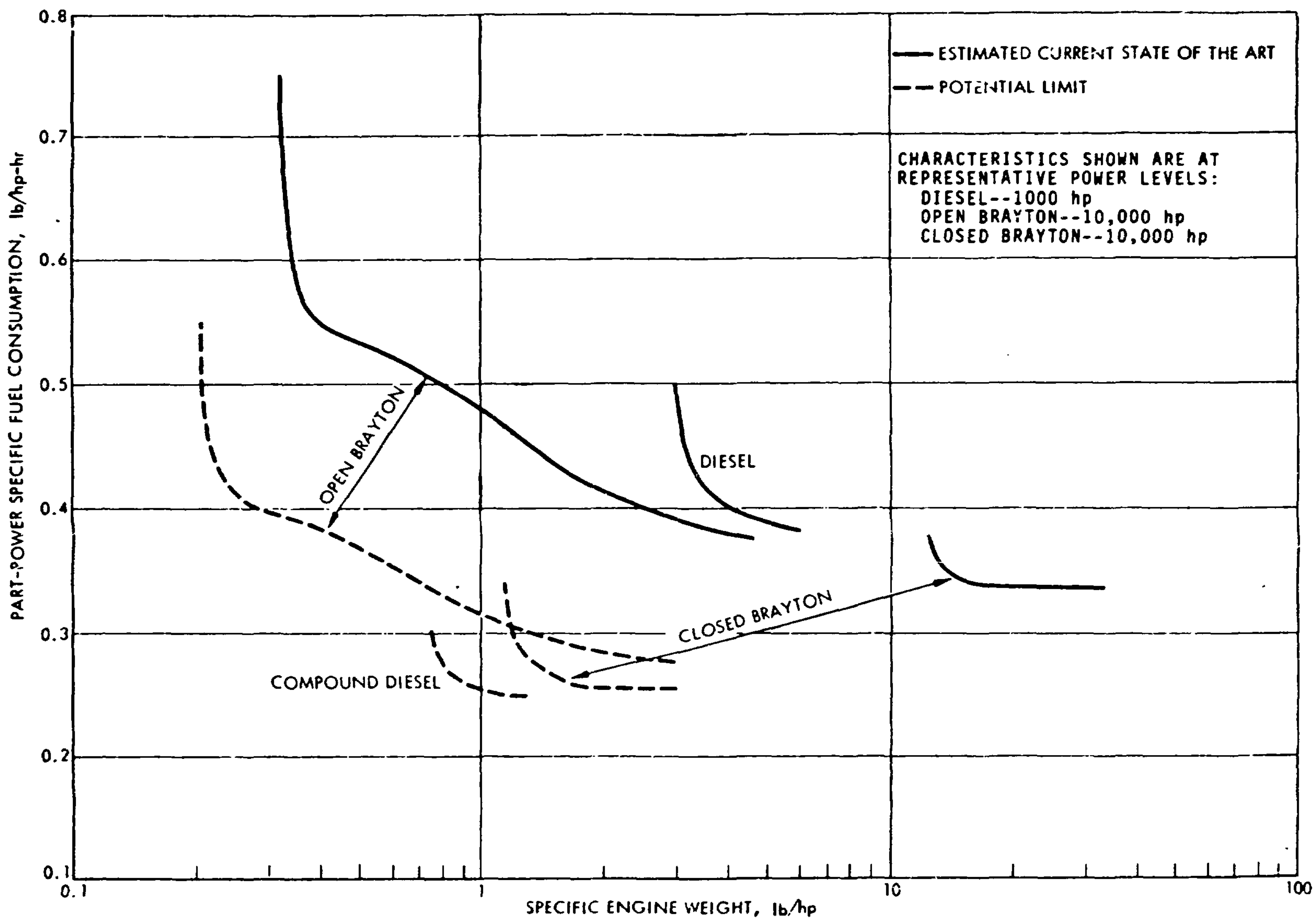

FIGURE III-3. Engine design characteristics.

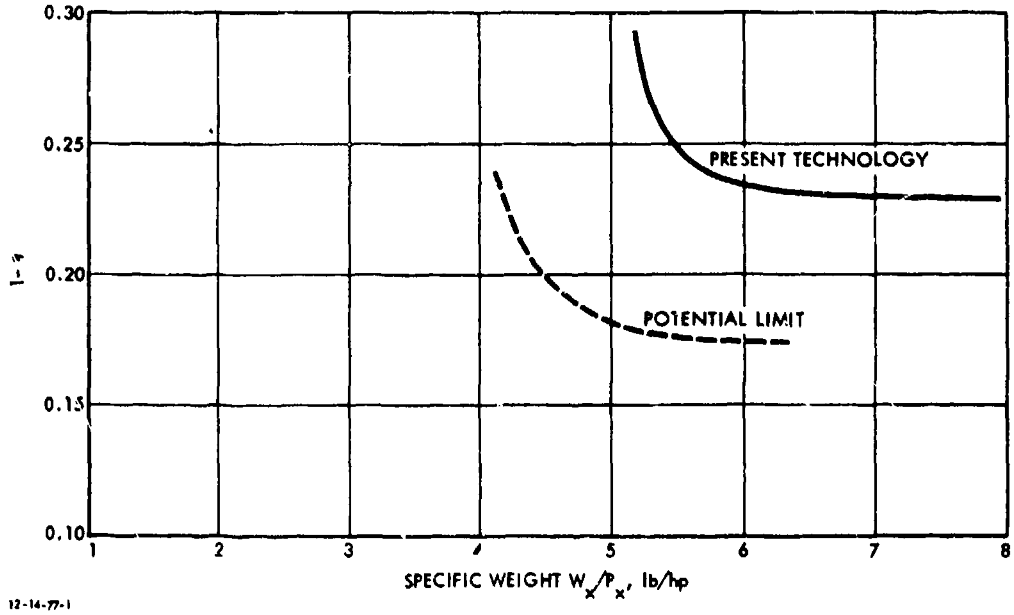

FIGURE III-4. Efficiency and specific weight characteristics for an MBT hydrodynamic transmission (including final drive).

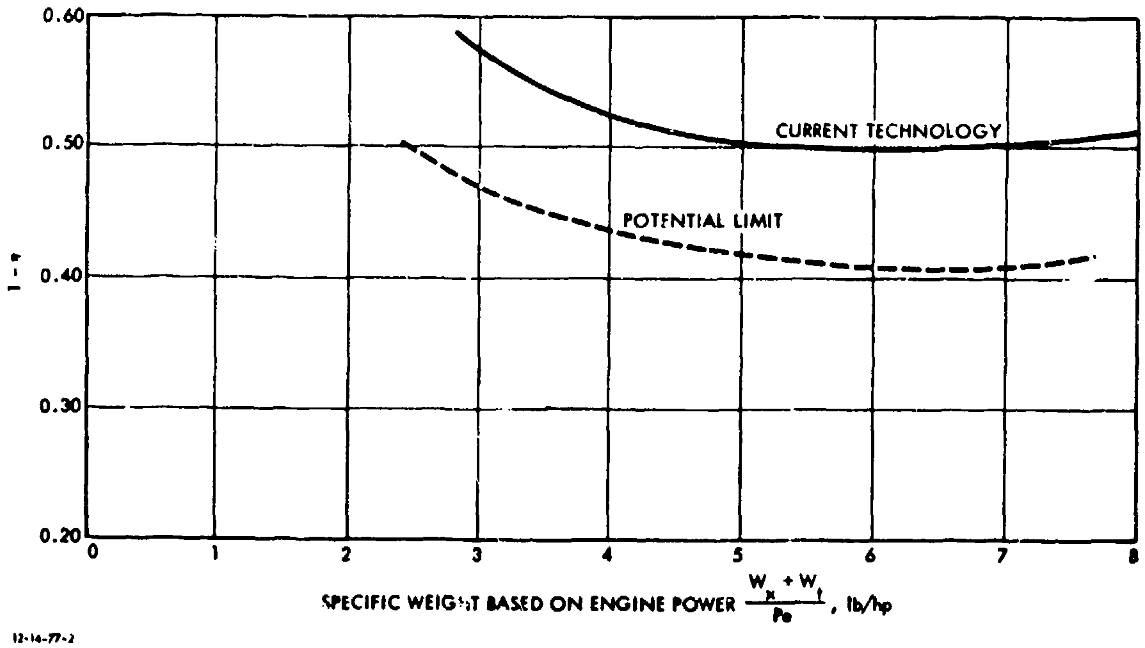

FIGURE III-5. Efficiency and specific weight characteristics for a mechanical transmission/waterjet combination. Representative power level: 10,000 shaft horsepower.

and hence will differ from the more conventional ones reported at either maximum power or best efficiency.

TABLE III-1. INSTALLATION FACTORS AND POWER ADJUSTMENTS FOR SUBSYSTEM CHARACTERISTICS

Diesel Engines in MBTs or Light LCVs:

$$\text{Installation Factor} = \frac{\text{Installed Weight or Volume}}{\text{Uninstalled Weight or Volume}} = 1.2$$

Cooling Power Adjustment, Current State of the Art

$$\frac{sfc_{e,net}}{sfc_{e,gross}} = \frac{sw_{e,net}}{sw_{e,gross}} = \frac{sv_{e,net}}{sv_{e,gross}} = 1.11$$

Gas-Turbine Engines in MBTs or Light LCVs:

Installation Factor = 1.3

Fuel Consumption Adjustment

sfc_e = 1.18 sfc @ 10,000 hp, current state of the art

sfc_e = 1.10 sfc @ 10,000 hp, potential limit

Gas-Turbine Engines in HSSs:

Installation Factor = 1.3

Closed-Brayton-Cycle Engines in HSSs:

Installation Factor = 1.2

For engines, specifically, the characteristics of the Diesel engine are based, per convention, on gross horsepower output; to be used in this analysis, the characteristics must be adjusted to account for the power required to cool the engine (typically, of the order of 10%). For gas-turbine (open-Brayton-cycle) engines, the characteristics are those for a nominal power level of 10,000 hp; to apply to power levels of 1,000 hp or so

(representative of MBT or light LCV applications), the specific fuel consumption shown in Fig. III-3 should be increased by approximately 10%. These various adjustments are listed in Table III-1.

The hydrodynamic transmission efficiency shown in Fig. III-4 includes the effect of the power required to cool the transmission (typically of the order of 4%, of the input power), and hence will be lower than conventionally reported values. These characteristics also include the so-called final drive used in MBTs and light LCVs, which by definition here is part of the transmission subsystem. The characteristics shown are applicable to power levels in the range of 1000 hp and input speeds in the range of 3000 rpm. The latter necessitates a correction when applied to gas-turbine engines, since an additional speed reduction is required; this is estimated to be about 0.2 lb/hp currently, with a potential limit of 0.1 lb/hp. As mentioned previously, the characteristics for transmission/waterjet thruster combinations shown in Fig. III-5 are based on the selection of an optimum transmission output speed, and are applicable to power levels in the vicinity of 10,000 hp.

Finally, to handle thrusters for LCVs (tracks or wheels), the weight and efficiency can be treated as independent of each other. It is shown in Appendix K that the weight of LCV thrusters is determined by the gross vehicle weight (GVW). For both MBTs and light LCVs, track-laying thrusters using current technology are about 22% of GVW. The efficiency of these systems, for our purposes here, can be taken as nearly constant. The losses were estimated at 5% in frictional resistance and 4% in slip.

These subsystem characteristics, subject to the modifications indicated, are the basis for the analysis here; when combined in the manner described previously, they produce the propulsion system characteristics used in Section II. Using these characteristics and the propulsion system goals established

in Section II in the manner also described above, goals and payoffs for the individual subsystems have been determined.

C. OVERVIEW OF SUBSYSTEM GOALS

Although subsystem goals and associated payoffs depend upon the specific vehicle application, and hence must be discussed in such a context to be fully appreciated, it is nevertheless instructive to examine the goals as they relate to individual types of subsystems. Accordingly, the resulting suitable R&D goals for engines are shown graphically in Fig. III-6 (for diesel engines in MBT and light LCV applications), Fig. III-7 (for gas-turbine engines in MBT, LCV, and HSS applications), and Fig. III-8 (for closed-Brayton-cycle engines in HSS applications). Similarly, suitable R&D goals for transmission and/or thrusters are shown in Fig. III-9 (for hydrodynamic transmissions in MBT or LCV applications) and Fig. III-10 (for mechanical transmission and waterjet combinations in HSS applications). In all of these figures, only specific fuel consumption and specific weight characteristics are shown, as a matter of convenience. It is to be noted at the outset that all goals for a given application and propulsion system are a related set, and hence the goals for a given type of subsystem (e.g., diesel engines in MBTs) depend upon the goals for the other related subsystems (e.g., hydrodynamic transmissions in MBTs). Further, for convenience, the installation factors have been removed, and the goals are hence referred to the uninstalled subsystems.

Referring first to suitable goals for Diesel engines (Fig. III-6, the areas shown are bounded by those characteristics which would result in either a 20 or 25% reduction in the vehicle cost/payload measure (in conjunction of course with the corresponding transmission goals). The slopes of these lines merely reflect the relative importance of specific fuel consumption as opposed to specific weight and specific volume (it has been assumed that the engine density is constant, and hence

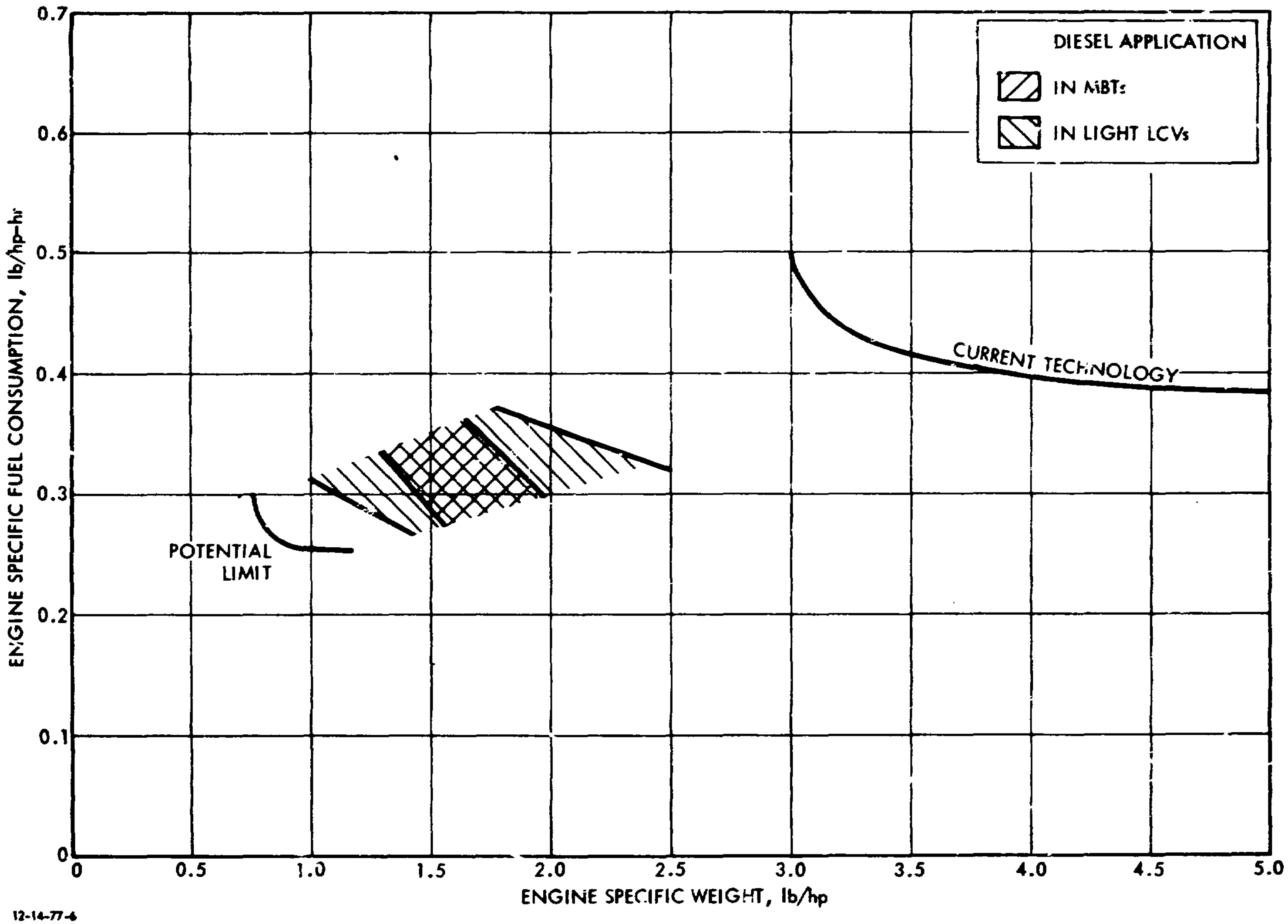

FIGURE III-6. Suitable R&D goals for diesel and compound diesel engines for two different applications.

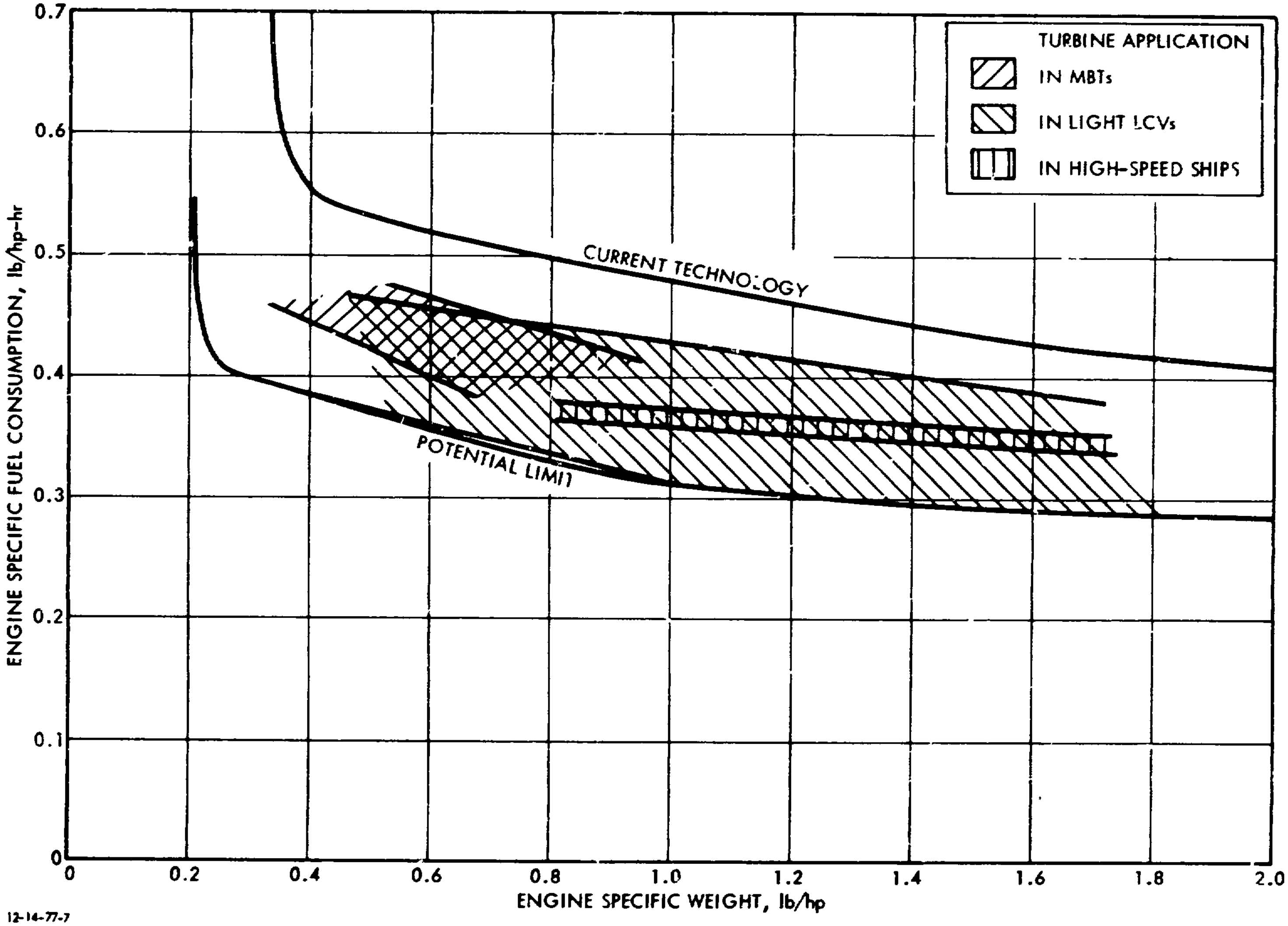

FIGURE III-7. Suitable R&D goals for tu-bine engines for three different applications.

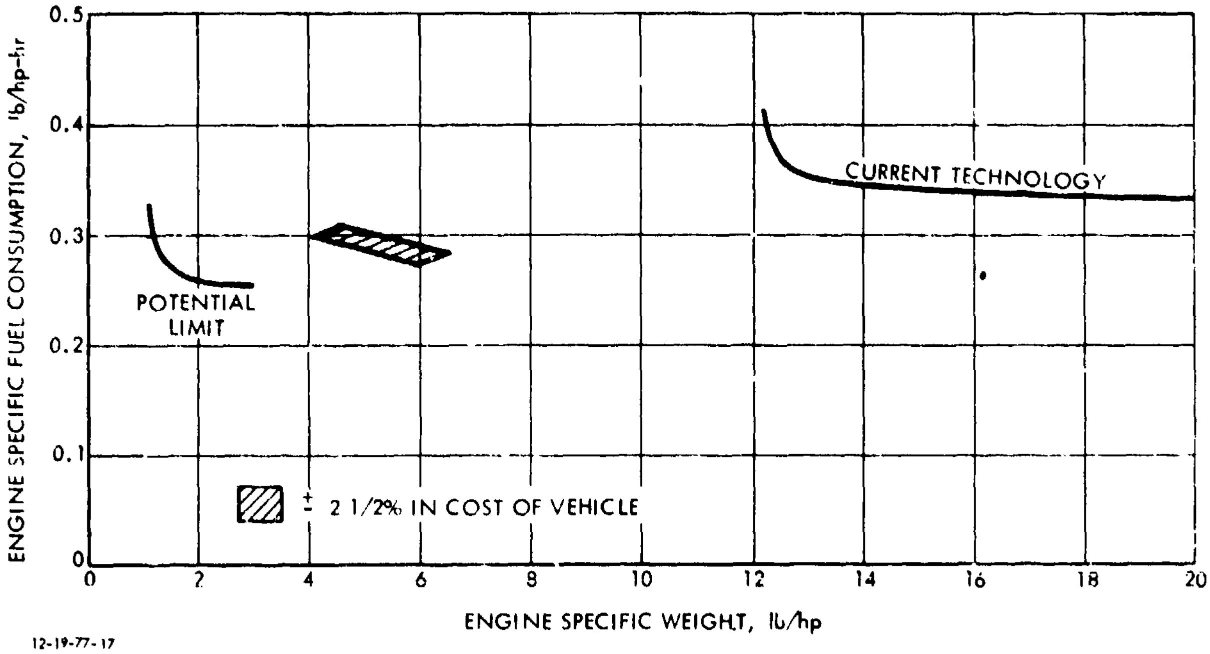

FIGURE III-8. Suitable R&D goals for closed Brayton-cycle engines for high-speed ships.

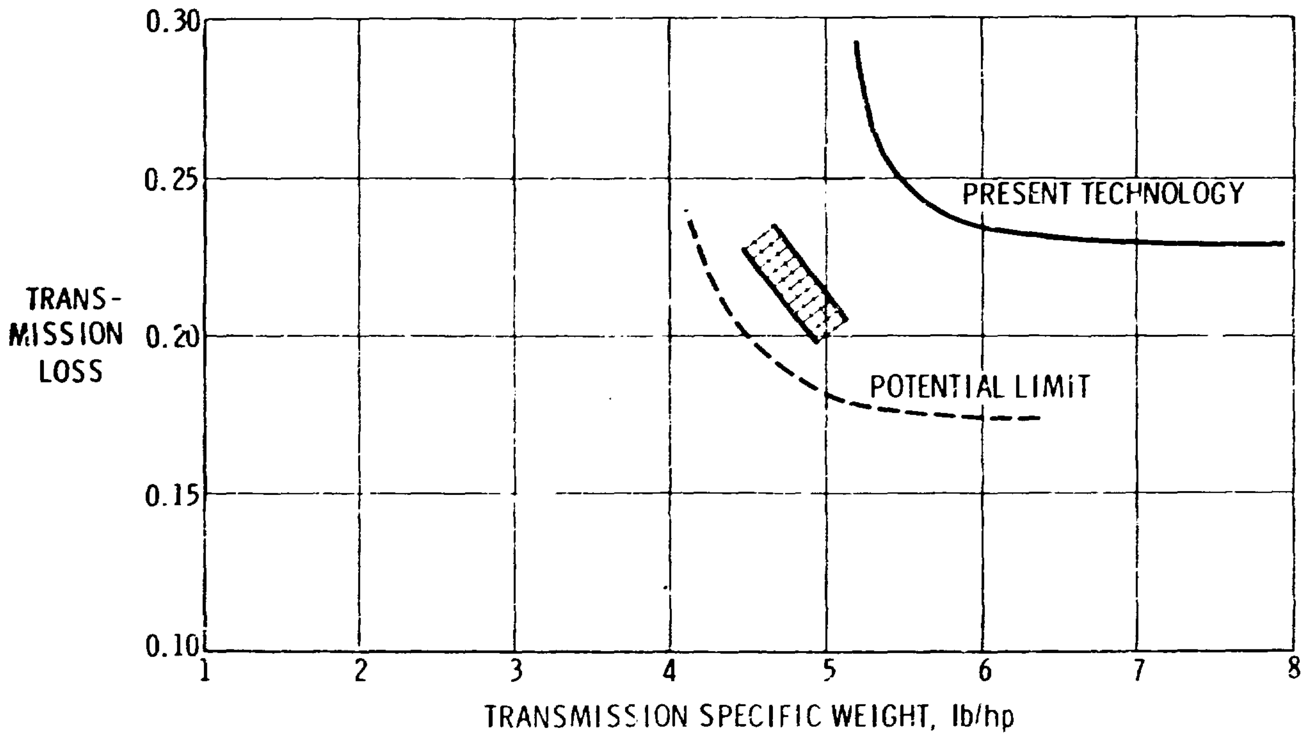

FIGURE III-9. Suitable R&D goals for hydrodynamic transmissions in main battle tank and light land combat vehicle applications.

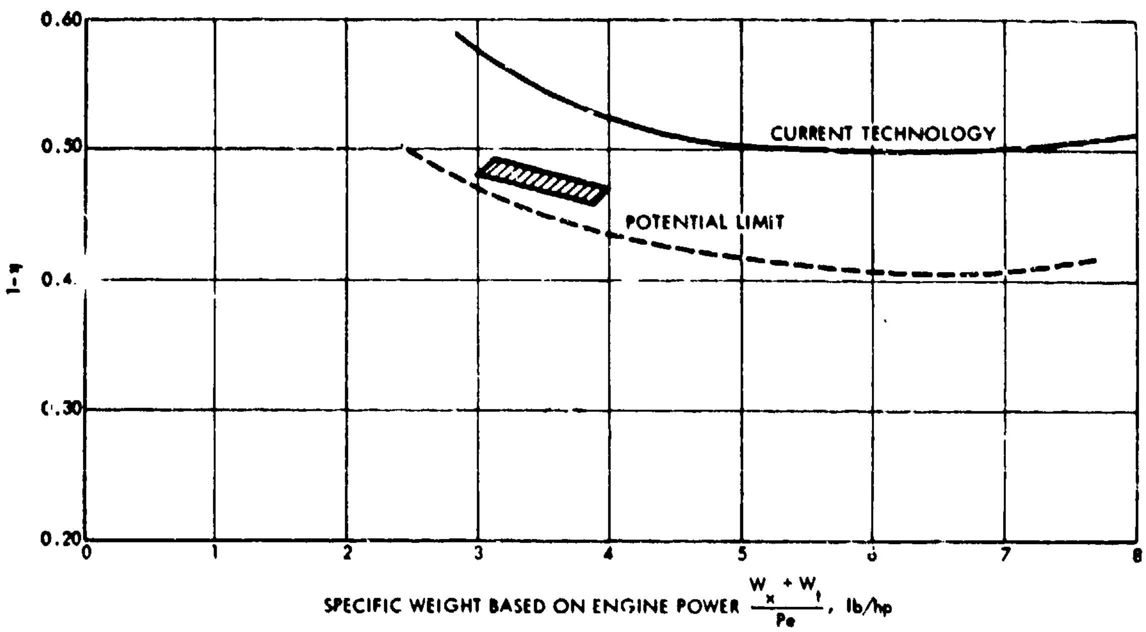

FIGURE III-10. Suitable R&D goals for a mechanical transmission/waterjet combination in high-speed ship applications.

specific volume varies linearly with specific weight) in the given application. Thus, the figure indicates that engine weight and size are relatively more important in MBT applications than in light LCV applications. It can be observed that the goals for either application overlap considerably, and hence in this case the two applications can be satisfied by essentially one set of goals. The broader region associated with light LCVs is merely a reflection that the overall propulsion system is of less importance in a light LCV than in an MBT, and hence greater changes in propulsion system characteristics are required to make the same vehicle impact. Finally, it can be observed that suitable goals represent a substantial departure from the present state of the art; rather large improvements are required if a significant impact on the vehicle cost/payload is to be made.

For gas-turbine engines, the goals shown in Fig. III-7 indicate again an appreciable overlap between MBT and light LCV applications,* but essentially none at all between MBT and HSS applications. Here, in the HSS application the area shown bounds a 5% change in vehicle cost/payload and is thus consistent with the other areas shown. The narrowness of the area in the HSS application merely reflects the larger impact which the overall propulsion system has on the vehicle. This in turn is due to the long range required of the vehicle, which is reflected by the relative importance of sfc as compared to specific weight, as indicated by the very small slope of the bounds. This importance of sfc also accounts for the lack of overlap with MBT goals, as mentioned previously. It can again be observed that the goals require substantial improvements over the present state of the art.

*All of the goals have been referred to a nominal power level of 10,000 hp; for MBT and light LCV applications, the actual sfc goals (as well as the two curves) are 10% higher.

Suitable goals for closed-Brayton-cycle engines in the HSS application are shown in Fig. III-8. The slope of the bounding lines again indicates the importance of sfc in this application.

The transmission and/or thruster goals in Figs. III-9 and III-10 reflect essentially the same features as suitable goals for engines. The major difference is that the goals represent less of a departure from current state-of-the-art values. This is simply because their potential limits are estimated to be closer to the current state of the art than similar estimates for engines. It should be pointed out that although suitable goals for hydrodynamic transmissions are slightly different for MBT and light LCV applications, only one area is shown in Fig. III-9 purely as a matter of convenience.

Apart from the dependence upon the specific application, it is also worth bearing in mind that these individual subsystem goals also depend upon the impact criterion selected, the estimated potential limits, and the other related subsystems. If less impact on the vehicle is acceptable as a criterion, then all subsystem goals will of course shift toward their current state-of-the-art values. If the potential limits of a subsystem were estimated to be closer to the current state of the art, then the relevant goals would shift toward the current values, but all subsystem goals would be relatively closer to their respective estimated potential limits.

D. SUBSYSTEM GOALS AND PAYOFFS FOR SPECIFIC VEHICLE CLASSES

As indicated earlier, the individual subsystem goals do not give any indication of the relative payoff associated with each one; hence the relative importance of achieving individual goals cannot be deduced. Further, the suitable goals put forth above can only be viewed as approximations; it is therefore of interest to be able to evaluate the suitability of other sets of proposed goals. To accomplish either of these, it is necessary to examine

the sensitivity of the vehicle to individual subsystem characteristics. Accordingly, it is convenient to complete this examination of subsystem goals and relative payoffs in terms of specific vehicle applications.

1. Main Battle Tanks

The sensitivity of the vehicle to individual subsystem characteristics is indicated by the subsystem cost sensitivity factors (the fractional change in vehicle cost/payload per unit fractional change in subsystem characteristic); these are shown in Table III-2 for the two propulsion systems applicable to main battle tanks.* Three features of these results are particularly noteworthy.

First, the characteristics with the highest leverage are, in order, thruster efficiency, transmission efficiency, and thruster weight. The origins are easy to explain since thruster efficiency, for a given output power, affects both engine and transmission size and weight in addition to overall fuel consumption; similarly, the transmission affects engine size and weight in addition to overall fuel consumption; and the thruster, which by definition here includes the suspension system, represents a large fraction of the total vehicle weight. Obviously, any improvement in these three characteristics would pay off handsomely.

The second feature is the potential importance of specific costs, particularly in engines; this is of course entirely consistent with the potential importance of specific costs of the total propulsion system in main battle tanks, as discussed in Section II. Here, for example, the results in Table III-2

*As discussed earlier, subsystem sensitivity factors depend upon the location of each subsystem relative to its current state-of-the-art and potential-limit characteristic curves; the sensitivities here are those applicable to the current vehicle and propulsion systems.

TABLE III-2. SUBSYSTEM COST SENSITIVITIES FOR MAIN BATTLE TANKS

Subsystem/Characteristic (Q)	Sensitivity Factor = $\frac{\Delta\$/\$}{\Delta Q/Q}$ Diesel System	Turbine System
Engine		
Specific Fuel Consumption (sfc_e)	0.17	0.23
Specific Weight (sw_e)	0.16	0.097
Specific Volume (sv_e)	0.13	0.085
$sw_e + sv_e$*	0.29	0.18
Specific Procurement Cost	0.10	0.097
Specific Maintenance Cost	0.20	0.19
Hydrodynamic Transmission		
Efficiency (η_x)	0.76	0.70
Specific Weight (sw_x)	0.15	0.17
Specific Volume (sv_x)	0.052	0.06
$sw_x + sv_x$*	0.20	0.23
Specific Procurement Cost	0.067	0.066
Specific Maintenance Cost	0.13	0.13
Thruster (Tracks and Suspension)		
Efficiency (η_t)	1.16	1.13
Specific Weight (W_t/W_v)	0.46	0.46
Specific Procurement Cost	0.05	0.05
Specific Maintenance Cost	0.10	0.10

*Indicative of a change in either specific weight or specific volume if the density is constant.

indicate that maintenance cost associated with diesel engines has slightly more leverage than specific fuel consumption, specific weight, or specific volume. Although such costs are assumed to be unchanging here, any proposed concepts which offer a reduction could accept somewhat less ambitious goals in the other characteristics, and achieve the same impact on the vehicle. For example, for the same impact, a 20% decrease in specific maintenance cost would permit an sfc goal to be relaxed by 17%. On the other hand, proposed concepts which might result in increases in specific costs would have to offer more ambitious goals in the other characteristics to achieve the same impact.

Finally, the sensitivity factors indicate differences among propulsion system types. For example, the engine specific fuel consumption is a more important characteristic in a turbine engine system than in a diesel engine system, and the engine specific weight and specific volume are less important--a direct result of the fact that the turbine engine is smaller and lighter and consumes more fuel than a diesel. Similarly, the compactness of the turbine results in the transmission size and weight being somewhat more important in this system than in the Diesel system. Inasmuch as these relative sensitivities are determined by the relative performance characteristics of the individual subsystems, they vary with the state of technology. Inasmuch as the suitable goals developed here encompass more improvement in engines than in transmissions, achievement of such goals would then result in a relatively higher leverage associated with the transmission than indicated by these current state-of-the-art values.

Although these cost sensitivities give some indication of the relative leverage of improvements in subsystem characteristics, they do not of course provide a measure of the potential unless they are combined with an assessment of the scope for improvement. Such potential impacts are shown in Table III-3 for MBT applications, where the cost impact associated with

changing each individual subsystem characteristic from its current value to a nominal goal value is shown. The goals for engine and transmission are treated together, and hence their combined impact is about a 23% reduction in vehicle cost/payload--midway in the 20-25% range used as a criterion here. As discussed in Section II, the thruster is treated separately, because it lies outside the armored volume and further provides the non-propulsive function of supporting the vehicle.

TABLE III-3. RELATIVE PAYOFFS OF SUBSYSTEM GOALS IN MAIN BATTLE TANKS

Subsystem/Characteristic	Diesel System: Current Value/Goal	Diesel System: Cost Impact of Goal	Turbine System: Current Value/Goal	Turbine System: Cost Impact of Goal
Engine				
sfc_e, lb/hr-hp	0.44/0.32	0.04	0.6/0.47	0.04
sw_e, lb/hp	4.3/1.9	0.08	2.6/0.78	0.06
sv_e, ft^3/hp	0.09/0.05	0.06	0.05/0.02	0.06
Transmission				
η_x	0.76/0.782	0.02	0.76/0.784	0.02
sw_x, lb/hp	6.6/4.7	0.02	6.6/4.75	0.04
sv_x, lb/hp	0.06/0.04	0.01	0.06/0.04	0.01
Total Cost Impact		0.23		0.23
Thruster, W_t/W_v	0.22/0.15	0.14		0.14

Note: Goals are expressed in terms of installed values; see Table III-1 for conversion for uninstalled values.

Inspection of the results in Table III-3 readily reveals the high-payoff R&D areas associated with main battle tank applications. The greatest payoff arises from reaching the

suitable goals developed for engines, as opposed to those developed for transmissions (in the ratio of 18 to 5 for the diesel system and in the ratio of 16 to 7 for the turbine system). This is a direct result of the fact that the scope for improvement in size, weight and efficiency was judged to be less than that for heat engines. The underlying reason for such a judgment is that the heat engines can benefit in both size and efficiency from advances in high-temperature material technology, whereas the transmission can benefit only in size from improved material properties. It can also be observed in Table III-3 that, for engines, specific weight and specific volume improvements have substantially more potential impact than specific fuel consumption improvements (in the ratio of 14 to 4 for the diesel and in the ratio of 12 to 4 for the turbine). This of course is a direct result of the potential improvements in weight and volume being judged to be considerably larger, percentagewise, than those in specific fuel consumption, in combination with the relative importance of these characteristics in the basic vehicle.

A major implication of these results is of course that if broad choices among R&D programs are necessary, then, for main battle tank applications, programs aimed at improving engines deserve greater consideration than programs aimed at improving transmissions (assuming other things, such as risks, are equal)--the potential impact is largest for engine improvements. Further, considering engines only, programs which address specific weight and specific volume improvements in preference to specific fuel consumption offer the greater payoffs. Both of these observations apply to either Diesel engines or turbine engines, although as might be expected the potential payoffs for turbine engine improvements appear to be slightly less.

In any event, if the criterion of significant impact used here--20-25% reduction in vehicle cost per unit payload at fixed performance--is judged to be a fair one, then such R&D programs

should be aimed toward goals equivalent to those established here. Obviously, the goals developed are intended to provide only reasonable guides to desirable improvements; they cannot be considered unique, as there are other sets of goals that may be equally acceptable, nor can the goals here be considered absolute, considering the various judgments and uncertainties involved. Indeed, the results presented in Tables III-2 and III-3 permit the evaluation of other sets of subsystem goals--either for the same types of subsystems considered here or for different types of subsystems--with respect to the vehicle cost per unit payload criterion.

2. <u>Light Land Combat Vehicles</u>

The subsystem cost sensitivity factors relevant to light LCV applications are shown in Table III-4. The highest leverage characteristics are identical to those for main battle tanks--thruster efficiency, transmission efficiency, and thruster weight. It can also be observed that, consistent with the lighter armor of these vehicles and the relatively greater importance attached to range, the engine specific fuel consumption has relatively greater leverage than engine size and weight.

The resulting payoffs associated with the individual goals are shown in Table III-5. It is to be noted that the goals shown are identical to those for main battle tanks, since they provide adequate payoff. The lower power level of this application (of the order of 500 horsepower engine output) may make the goals for the turbine engine somewhat more difficult to reach than the same goals for the higher power-level main-battle-tank application. The payoffs shown in the form of cost impacts are somewhat deceptive in this case; it will be recalled that the propulsion system representative of the current vehicle is an older Diesel system, and there is no turbine counterpart. Hence the cost impacts, for the Diesel system, reflect those due to the change from older propulsion system technology, rather than

TABLE III-4. SUBSYSTEM COST SENSITIVITIES FOR LIGHT LCVs

Subsystem/Characteristic (Q)	Sensitivity Factor = $\frac{\Delta\$/\$}{\Delta Q/Q}$ Diesel System	Turbine System
Engine		
Specific Fuel Consumption (sfc_e)	0.16	0.20
Specific Weight (sw_e)	0.13	0.074
Specific Volume (sv_e)	0.03	0.019
$sw_e + sv_e$	0.16	0.093
Specific Procurement Cost	0.087	0.087
Specific Maintenance Cost	0.17	0.17
Hydrodynamic Transmission		
Efficiency (η_x)	0.57	0.56
Specific Weight (sw_x)	0.12	0.13
Specific Volume (sv_x)	0.012	0.013
$sw_x + sv_x$	0.13	0.14
Specific Procurement Cost	0.059	0.059
Specific Maintenance Cost	0.12	0.12
Thruster		
Efficiency (η_t)	0.88	0.87
Specific Weight (w_t/W_v)	0.43	0.43
Specific Procurement Cost	0.04	0.04
Specific Maintenance Cost	0.08	0.08

from current technology, to the goal values. For the turbine system, the cost impacts further include the change in type of system--thus the cost impact of engine sfc is shown to be negative, reflecting the fact that the goal for a turbine engine is higher than that of the older Diesel. To be totally consistent with the spirit of this investigation, it would be appropriate to formulate the goals on the basis of current technology. Due to the rather smaller impact of the propulsion system on this class of vehicles, this would produce more stringent goals than for main battle tanks. For precisely the same reason--the smaller impact of the propulsion system--such goals would be of dubious value; the more logical course would seem to be to pursue goals appropriate to both applications, with the understanding that the impact on light land combat vehicles is somewhat less than the 20-25% for main battle tanks.

TABLE III-5. RELATIVE PAYOFFS OF SUBSYSTEM GOALS IN LIGHT LCVs

	Diesel System		Turbine System	
Subsystem/Characteristic	Current Value/Goal	Cost Impact of Goal	Current Value/Goal	Cost Impact of Goal
Engine				
sfc_e, lb/hp-hr	0.42/0.32	0.05		(0.02)
sw_e, lb/hp	8.8/1.9	0.11		0.17
sv_e, ft^3/hp	0.18/0.05	0.03		0.04
Transmission				
η_x	0.76/0.782	0.02		0.02
sw_x, lb/hp	5.7/4.7	0.02		0.02
sv_x, lb/hp	0.06/0.04	0.0		0
Total Cost Impact		0.23		0.23
Thruster, W_t/W_v	0.33/0.15	0.13		0.13

Note: Goals are presented in terms of installed values; see Table III-1 for conversion to uninstalled values.

The same general priorities as those for main battle tanks are nevertheless evident in Table III-5. The relative importance of reaching the engine goals is much greater than that for transmissions, and hence R&D programs for engine improvements deserve first preference. The major difference with respect to the main battle tank application is the reduced importance of engine specific volume, which is a direct result of the lighter armor of the vehicle. As was the case for main battle tanks, the results presented in Tables III-4 and III-5 can be used to evaluate other equivalent sets of goals which might arise.

3. High-Speed Ships

The subsystem cost sensitivity factors relevent to high-speed ship applications are shown in Table III-6. It can be observed that the sensitivities here are entirely different from those associated with land combat vehicles. The specific volume of the subsystems is of virtually no importance in this application, and is omitted from the table. The sensitivities of the fuel consumption characteristics--sfc_e and $\eta_x\eta_t$--are completely dominant, arising from the long-range requirement of the vehicle. Further, the specific cost characteristics are of rather minor importance, since the propulsion system costs represent a much lesser fraction of vehicle costs than in land combat vehicles.

It will be recalled that there are no rational (in the sense used here, namely a sufficiently low cost per unit payload) high-speed ships in service. This prevents the use of the cost impact of reaching a subsystem goal as a meaningful measure of impact, since there is no rational place from which to start. Nevertheless, the cost impact associated with reaching a subsystem goal from the current value can be determined in the usual way, and these are shown in Table III-7. Such payoffs do provide an indication of the relative importance of reaching the subsystem goals, but it must be emphasized that they are not a measure of impact on a rational vehicle.

TABLE III-6. SUBSYSTEM COST SENSITIVITIES FOR HIGH-SPEED SHIPS

Subsystem/Characteristic (Q)	Sensitivity Factor = $\frac{\Delta\$/\$}{\Delta Q/Q}$ Turbine System	Closed-Brayton System
Engine		
Specific Fuel Consumption (sfc_e)	1.29	0.80
Specific Weight (sw_e)	0.018	0.49
Specific Procurement Cost	0.037	0.036
Specific Maintenance Cost	0.073	0.072
Transmission/Thruster		
Efficiency ($\eta_x\eta_t$)	1.42	1.39
Specific Weight (sw_{xt})	0.14	0.16
Specific Procurement Cost	0.023	0.024
Specific Maintenance Cost	0.047	0.048

TABLE III-7. RELATIVE PAYOFFS OF SUBSYSTEM GOALS IN HIGH-SPEED SHIPS

Subsystem/Characteristic	Turbine System: Current Value/Goal	Turbine System: Cost Impact of Goal	Closed-Brayton System: Current Value/Goal	Closed-Brayton System: Cost Impact of Goal
Engine				
sfc_e, lb/hp-hr	0.55/0.35	0.47	0.36/0.29	0.15
sw_e, lb/hp	0.51/1.95	(0.05)	15.0/6.0	0.30
Transmission/Thruster				
$\eta_x\eta_t$	0.48/0.53	0.16	0.50/0.53	0.09
sw_{xt}, lb/hp	8.4/6.9	0.02	10.1/7.6	0.04

Note: Goals are expressed in terms of installed values; see Table III-1 for conversion to uninstalled values.

As might be expected, the priorities reflected in Table III-7 are quite different from the previous ones for land combat vehicles. For the turbine-engine system, the highest payoff is associated with reaching the sfc goal; the increase in specific weight (a negative payoff) shown merely reflects the fact that a highly regenerated engine to reduce the sfc, is preferable to the current nonregenerated one. A similar situation exists for the transmission/thruster combination; there is much greater payoff associated with increasing efficiency than in reducing weight.

For the closed-Brayton-cycle system, the engine situation is reversed, the relative payoff of engine weight reduction being greater than that of sfc reduction. This results because the engine is initially quite heavy and relatively efficient, and there is judged to be far more potential for weight reduction than for sfc improvement (see Fig. III-3). As a consequence, weight reduction in the transmission/thruster becomes relatively more important than efficiency improvement, as compared to the turbine-engine system--even though, as indicated in Table III-7, the design point for the subsystem will lie toward slightly higher values of weight and efficiency for the closed-Brayton system, simply because the engine is heavier.

As for the previous applications, the results in Tables III-6 and III-7 can be used to evaluate other sets of subsystem goals which might arise.

IV. TECHNOLOGY IMPACT ON PROPULSION SUBSYSTEMS

The suitable goals and high-payoff areas for propulsion subsystems developed in the preceding section are based upon subsystem performance characteristics for both current state-of-the-art capabilities and potentially limiting capabilities. In this section, these performance characteristics are developed successively for heat engines, transmissions, thrusters for off-road vehicles, and thrusters for high-speed ships, and the technology impacts needed to achieve the goals are examined.

A. HEAT ENGINES

1. General Considerations

The objectives of the present investigation of heat engines are (1) to identify suitable goals and/or high-payoff areas of technology for some known types of heat engines, and (2) to provide a framework for evaluation of more general (and non-specific) heat-engine concepts. As previously discussed, the heat-engine characteristics of primary concern here are the specific fuel consumption (sfc_e), the specific weight (sw_e), and the specific volume (sv_e). Goals for heat engines in these terms, as presented in the previous section, are based on the analyses of the sfc_e-sw_e-sv_e relationships developed here.

a. Approach. The problem of identifying rational goals for needed advances in engine technology is neither new nor easy. Some of the more pronounced difficulties are that: first, there are a wide variety of engine types and cycles, some known and presumably some as yet undiscovered, which may require consideration; second, the details of specific engine design and operation are complex; and third, the prospects for

technology improvement are, at best, uncertain and, at worst, may not match needed advances.

The approach used here is to dissect and quantify sfc_e-sw_e-sv_e relationships for some specific engine types so as to expose (1) the physical origins and limits of the relationships, (2) the fundamental similarities and differences among various types of engines, and, as a result, (3) the physical limits and areas of opportunity for improvement in engines. Four elements constitute the approach:

1. Relating the ideal performance of various engine cycles to parameters which characterize the various power transfers which take place in the engines.
2. Identifying the major loss mechanisms associated with the various power transfers, and quantifying their impact by relating actual performance to ideal performance in terms of these losses and the associated power transfers.
3. Examining the relationship among losses, specific weight, and specific volume for the various components used to effect the power transfers, assessing the current state of the art, and ascertaining their limits.
4. Synthesizing the sfc_e-sw_e-sv_e for both the current state of the art and the projected potential limit for the various engine cycles.

It is believed that these four elements provide a uniform framework for evaluating future engine concepts on the basis of the particular improvements in power transfer and/or conversion processes and equipment which they may incorporate. Here, five engine types are evaluated, albeit in varying degrees, in this manner--Otto, Diesel, open Brayton, closed Brayton, and Stirling. In general, the details of these evaluations are presented in Appendices C through G; only the major results will be discussed here.

A basic premise in the approach is that the sfc_e-sw_e-sv_e relationship is strongly influenced by the magnitude and rate of energy transfer processes *internal* to the engine. The corollary is that energy and power transfer are useful and common characterizations of the physical origins of this relationship in any engine--past, present, or future. It seems obvious that power transfer can be directly related to weight or volume; it is quite conventional to refer to horsepower per pound or horsepower per cubic foot, for example, as important characteristics of not only engines but of other sorts of power transfer equipment as well (transmissions, compressors, turbines, pumps, etc.). What seems to be less conventional, however, is to relate power transfer to specific fuel consumption directly; usually, specific fuel consumption is related directly to such things as Carnot efficiencies, compression or pressure ratios, and temperature ratios. Although these quantities are useful in assessing physical limits and constraints in specific engine types, they do not directly relate to power transfer, and hence the relationship between specific fuel consumption, on the one hand, and specific weight and specific volume, on the other, is not readily apparent. Thus, considerable emphasis is placed here on portraying heat-engine performance in terms of appropriate power transfer parameters.

Characterizing engines in terms of the relevant energy/power transfer processes leads to the definition of the following power* transfers:

1. Inlet Power (P_1)--the power represented by the flow of the working fluid at its minimim temperature; for example, $P_1 = \dot{m}c_pT_1$ for a perfect gas with mass flow

*As used here, power is defined generally as energy flow per unit time, regardless of the form (mechanical work, heat, chemical change, etc.) of the energy transfer process.

rate $\dot{m}$, specific heat at constant pressure c_p, and minimum temperature T_1.

2. Internal Power Transfer (P_{int})--power transferred from processes subsequent to the initiation of heat addition in an engine to the pre-energy-addition process; for example, $P_{int} = \dot{m}c(T_2-T_1)$ for a perfect gas with mass flow rate $\dot{m}$, specific heat c, minimum working temperature T_1, and a temperature before combustion begins of T_2. By definition, the magnitude of the internal power transfer does not depend upon the manner (e.g., compression or heat exchange) by which it is achieved.
3. Power Addition (P_{add})--the rate of heat addition to the working fluid from the fuel; for example, $P_{add} = \dot{m}_f \Delta H$ for a fuel mass flow rate directly into the working fluid $\dot{m}_f$, and a heat of combustion ΔH.
4. Power Output (P_o)--The shaft power delivered by the engine.
5. Intermediate Power Transfer (P_x)--any other power transfer in the engine which requires mechanical devices; this includes heaters and waste-heat exchangers for closed-cycle engines, and the power received or added by heat exchange during compression or expansion processes (as in Stirling engines). The sum of the intermediate power transfer and the internal power transfer is denoted by the total internal power transfer, $P_{it} = (P_{int} + P_x)$.

The view here is that if engines with substantially better sfc_e-sw_e-sv_e characteristics are to be invented, then the origins of such improvements will be in: (1) changing the magnitudes of these power transfers appropriately; (2) decreasing the losses that are inevitably associated with these power transfers; and/or (3) improving the specific weight and volume characteristics of the components which are used to effect these power transfers. On the other hand, there are some physical limits and practical constraints applicable to all of these areas. The questions which are addressed here, then, are what must be done in the

way of modifying these power transfers, their losses, and associated equipment in order to make a substantial impact on the sfc_e-sw_e-sv_e relationship of engines, and what are the fundamental or practical limits to such modifications.

b. Ideal Engine Performance and Power Transfer. To illustrate the characterization of heat engines in terms of power transfers, the ideal performances of four cycles--Carnot, Otto, Brayton, and Stirling--are shown in Fig. IV-1. The performance characteristics are the specific fuel consumption* and the ratio of output power to inlet power (where the specific heat in the latter is taken as that appropriate to the compression process). The characteristics shown in Fig. IV-1 follow from the straightforward application of thermodynamic relationships. It is to be noted that the only assumption involved is that the working fluid is a perfect gas; the results as shown do not depend upon the values of specific heats or specific-heat ratios.

The major observation to be made is that the (ideal) specific fuel consumption depends only upon the internal power transfer ratio. This dependence is identical for all four cycles, indicating that (1) the sfc_e depends only on the magnitude of the ratio, and not upon the way (e.g., compression or heat exchange) in which it is achieved, and (2) decreasing the ideal sfc_e requires an increase in the internal power transfer ratio. The parameters of the specific power output characteristics in Fig. IV-1 are readily identifiable with physical limits or constraints. The normalized heat addition, for open cycles, is limited by the stoichiometry of the fuel in air, while the sum of the normalized heat addition and internal power transfer is indicative of the maximum temperature in an engine, and is limited by material properties.

*For a fuel with a heating value of 18,400 Btu/lb; the thermodynamic efficiency is related to the sfc by $\eta = 0.138/sfc_e$.

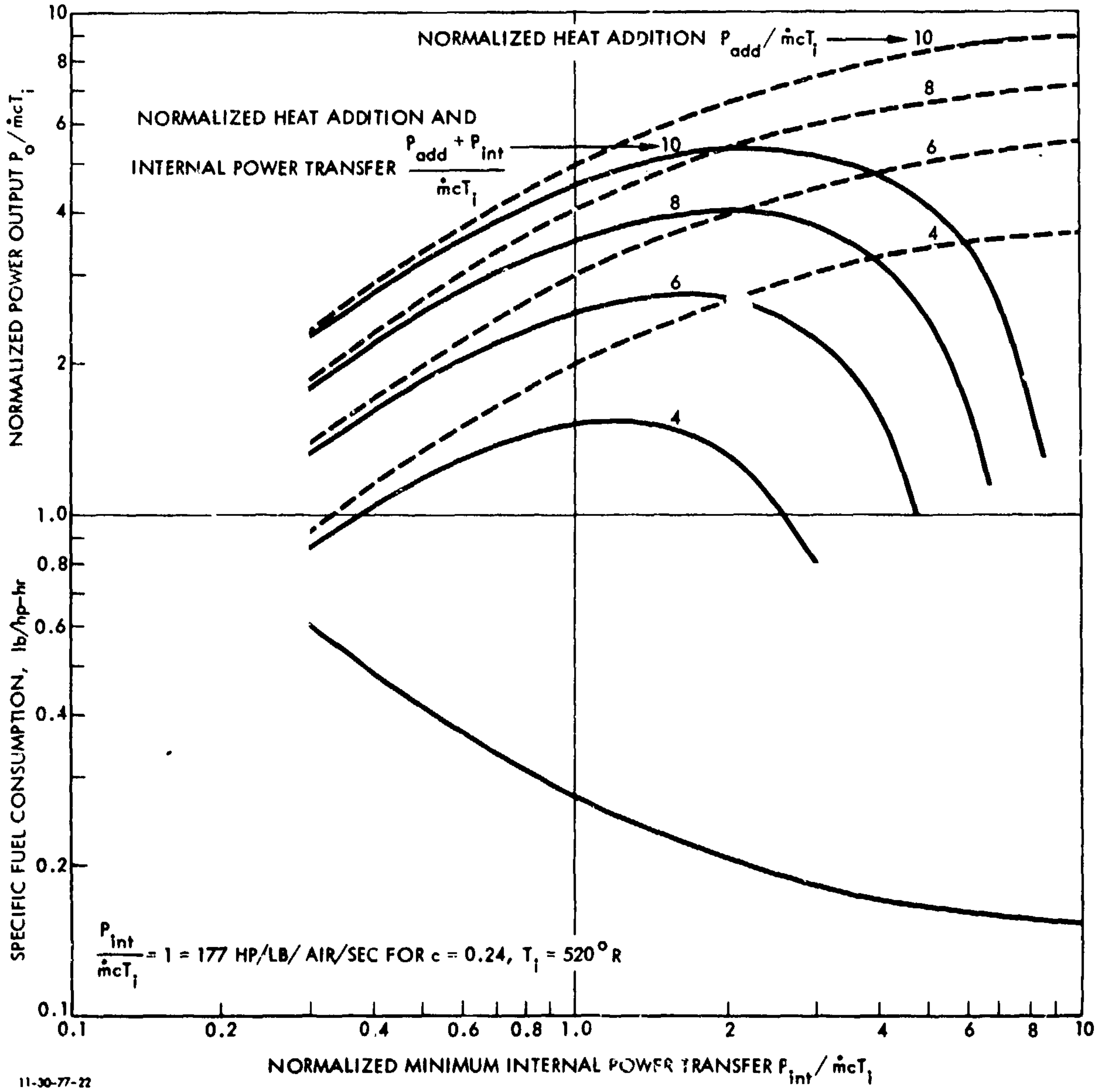

FIGURE IV-1. Ideal performance characteristics of Carnot, Otto, Brayton, and Stirling engines in terms of energy transfer parameters.

For the purposes of relating specific fuel consumption to specific weight and specific volume, Fig. IV-1 does not quite reflect the total importance of power transfers within an engine, since any intermediate power transfer should be included, and since the ratio of the total power transferred within an engine to its power output is a more correct reflection of the former. The ideal relationships can thus be portrayed more meaningfully, as in Fig. IV-2.

In Fig. IV-2, ideal performances of the following cycles are shown (all of which are developed in Appendices C through G):

1. Otto Cycle--for ratios of P_{add}/P_i of 8 and 10, and a ratio of specific heats, $\gamma = 1.4$; stoichiometric values of conventional hydrocarbon fuels burning in air are about $P_{add}/P_i = 9.3$.
2. Constant-Pressure Diesel Cycle--for ratios of P_{add}/P_i of 8 and 10, $\gamma = 1.4$.
3. Open Brayton Cycle--for ratios of $(P_{add} + P_{int})/P_i$ of 4 and 6. These ratios correspond to maximum temperatures of 2140°F and 3180°F for air as the working fluid at an inlet temperature of 60°F. These results apply to either simple or regenerated cycles, although there are of course some restrictions on the maximum amount of regeneration which is possible (i.e., the combustor inlet temperature cannot be higher than the turbine exhaust temperature).
4. Closed Brayton Cycle--for ratios of $(P_{add} + P_{int})/P_i$ of 3 and 5. These ratios correspond to maximum temperatures of 1620°F and 2660°F for a minimum working fluid temperature of 60°F. It is to be noted that the total internal power transfer includes that associated with heat addition and heat rejection.
5. Closed Stirling Cycle--for ratios of P_{int}/P_i of 3 and 5. These ratios again correspond to maximum temperatures

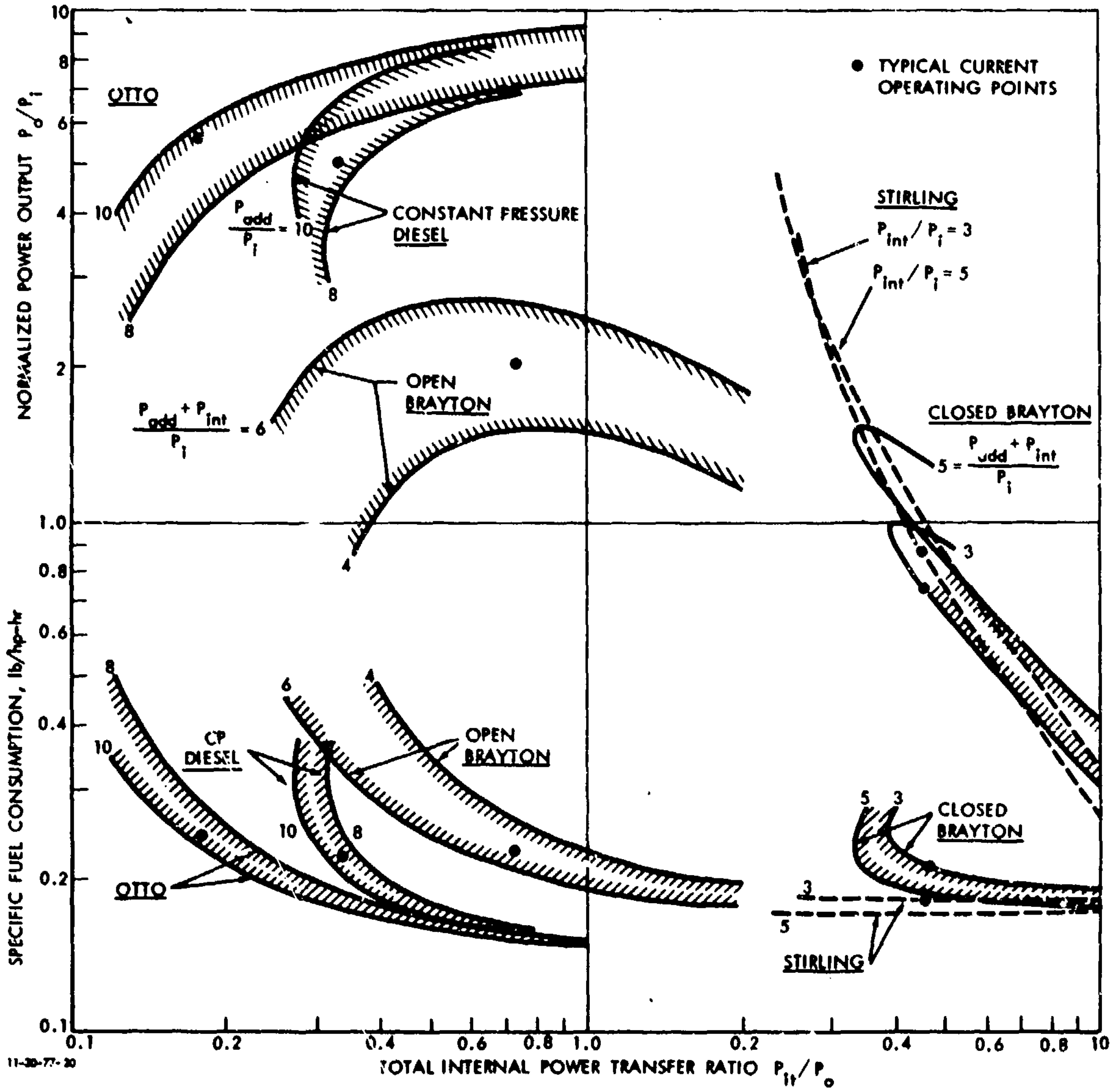

FIGURE IV-2. Ideal performance of Otto, constant-pressure Diesel, open Brayton, closed Brayton, and Stirling cycles as a function of total internal power transfer.

of 1620°F and 2660°F for a minimum working fluid temperature of 60°F. The total internal power transfer includes that associated with all heat addition and heat rejection.

The results in Fig. IV-2 portray some interesting characteristics of the various cycles. First, the Otto cycle is superior in two respects: for a given level of ideal sfc_e, it requires the least internal power transfer per unit output horsepower (current engines operate in the ideal range of 0.15-0.20 horsepower transferred internally per output horsepower); further, the Otto produces the maximum power output per unit of "inlet" power (current engines operate in the range of 5 to 6). Second, the closed cycles are inferior in the same two respects: they require (ideally) a total internal power transfer of 4-6 horsepower per output horsepower, and operate in the range of 0.5-1.5 horsepower output per unit of inlet power. Thus, not only do closed cycle engines require an order of magnitude more internal power transfer per unit power output than Otto cycles, but they also require about 5 times more mass flow per unit power output, other things being equal. It is evident from Fig. IV-2 that the latter property can be alleviated somewhat by the selection of a working fluid with a high specific heat (e.g., hydrogen or helium). Nevertheless, it can be anticipated that closed-cycle engines will be dominated by internal power-transfer equipment, and that the effect of losses associated with power transfers will be relatively much more important in these engines, since so much internal power transfer is required. It can also be observed in Fig. IV-2 that the impact of specific heat addition (constrained by stoichiometry or maximum temperature) on the ideal sfc is relatively small for all cycles; as will be seen subsequently, however, increased specific heat addition has an additional beneficial impact on the actual sfc by reducing the impact of the losses associated with the various power transfers.

From the view of evaluating other engine concepts, it seems clearly desirable (but not essential) that any proposed concept offer some advantage in performance characteristics over those displayed in Fig. IV-2. In any event, the nature of any proposed concept can be illuminated by determining these characteristics. Obviously, a complete evaluation of any concept requires consideration of losses and components associated with the various power transfers, as developed in the following sections for the five engine types considered here.

2. Spark-Ignition (Otto) Engines

a. Ideal Performance. The conventional Otto cycle consists of isentropic compression, combustion at constant volume, isentropic expansion, and heat rejection at constant volume. For a given fuel, the basic cycle parameters are the compression ratio and the fuel-air ratio. In terms of the power transfers used here, the internal power transfer is that required for compression, the power added is the heat-release rate from combustion of the fuel, and the power output is the difference between the power developed during expansion and that required for compression. The performance of the ideal cycle is shown in Fig. IV-3, w[illegible] it is to be noted that specific power additions (P_{add}/P_1) of [illegible] and 8 correspond to equivalence ratios (the ratio of the actual fuel-air ratio to the stoichiometric value) of approximately 1.08 and 0.86, respectively. It can be observed that improvements in ideal specific fuel consumption require large increases in compression ratio.

A major source of thermodynamic inefficiency in the ideal Otto cycle is the relatively high available energy content of the exhaust gases. Variations of the Otto cycle have been devised to utilize some of the exhaust energy, and three such ideal cycles are examined in Appendix C: the turbocharged Otto cycle, the regenerated Otto cycle, and the Lenoir cycle. The performance of the turbocharged cycle is shown in Fig. IV-4, where it is to be noted that the internal power transfer includes

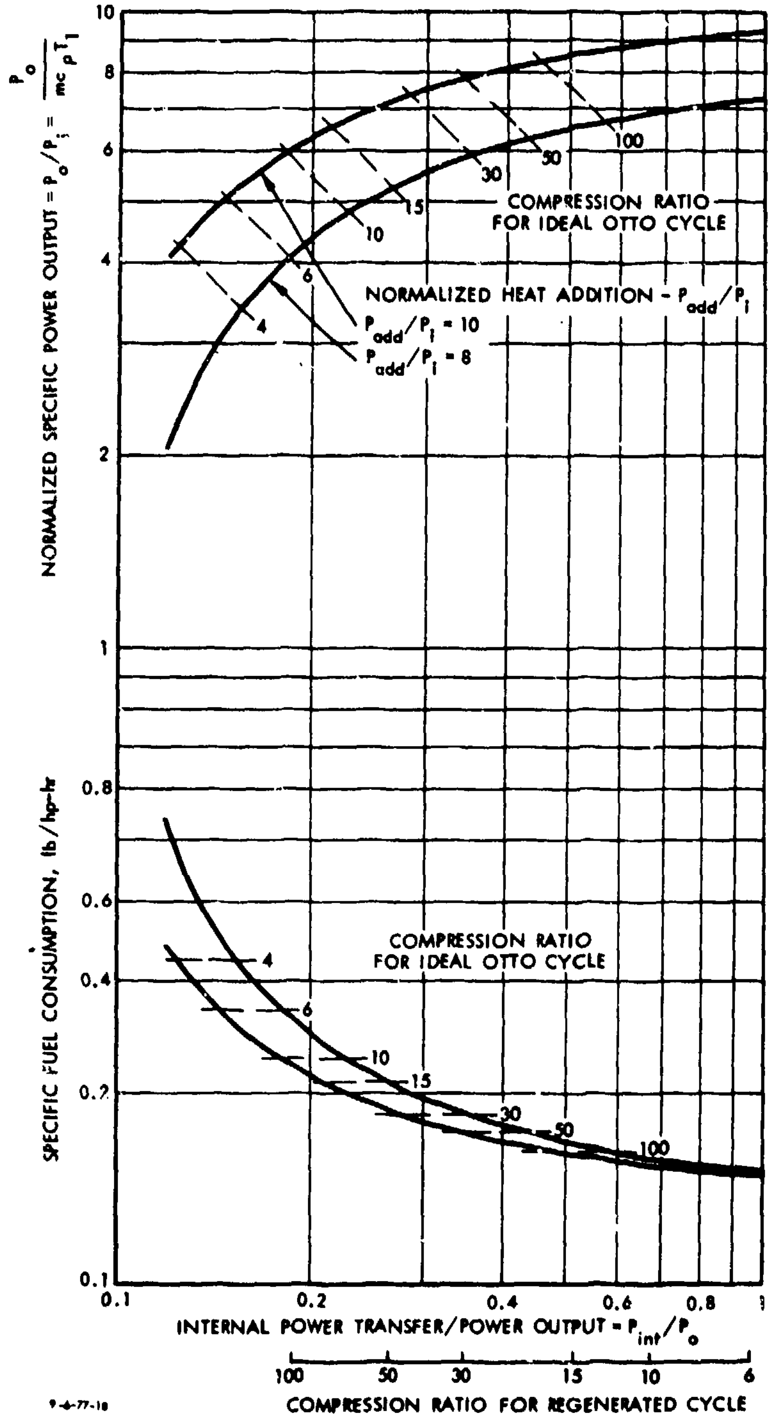

FIGURE IV-3. Performance of ideal Otto cycle.

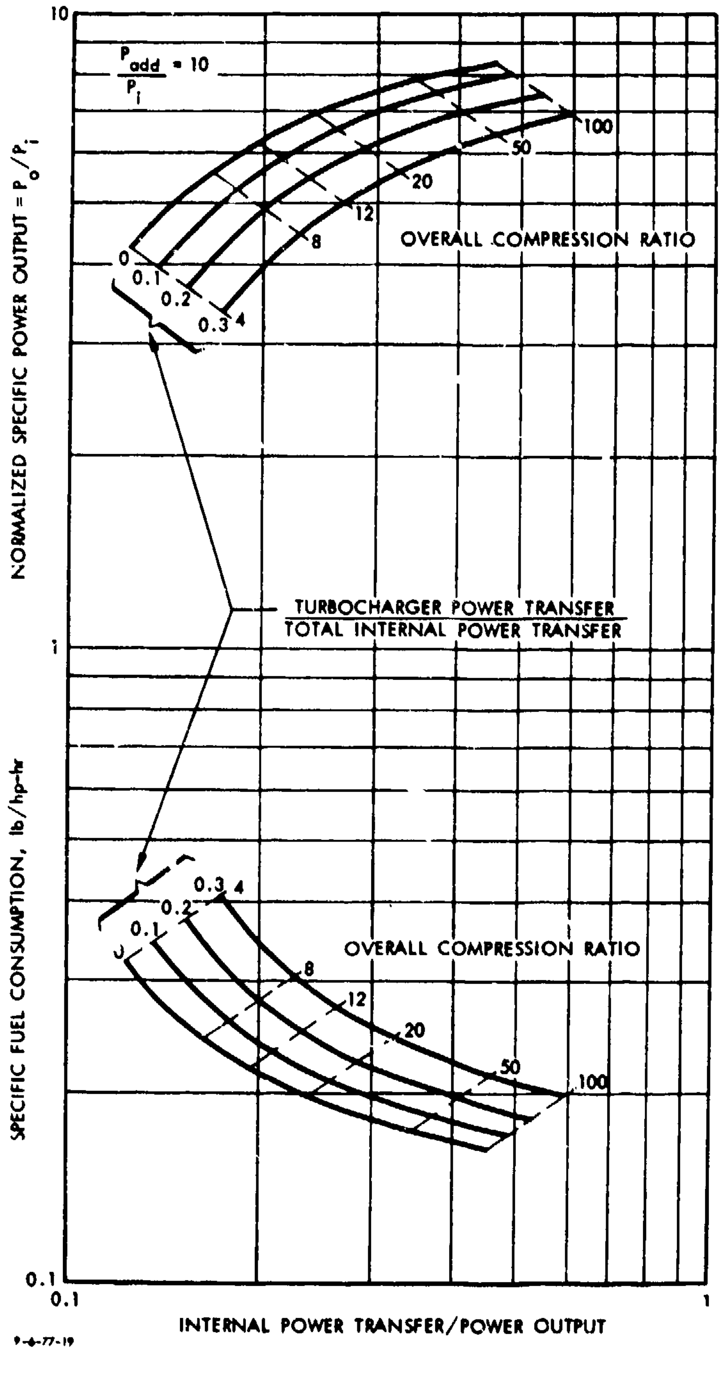

FIGURE IV-4. Performance of ideal turbocharged Otto cycle.

the power transfer through the turbocharger. It can be observed that turbocharging reduces the specific power output and increases the specific fuel consumption. As will become evident later, the primary advantage of turbocharging is in reducing the weight and size of the equipment necessary to accomplish the internal power transfer. The regenerated Otto and Lenoir cycles, as developed in Appendix C, have essentially the same performance characteristics as the conventional Otto cycle when expressed in terms of internal power transfer; their major advantage lies in reducing the compression ratio needed to accomplish the internal power transfer, but due to practical difficulties in implementation they are not considered further here.

With respect to further improvements in the ideal performance of Otto engines, present engines operate with stoichiometric mixtures, and thus no further increases in specific heat addition can be expected for engines which use air as the working fluid. It can be observed from the behavior of the ideal performance (Figs. IV-3 and IV-4) that further improvements must originate in increasing the ratio of internal power transfer to power output. Conventional Otto engines are limited by combustion (i.e., "knocking") considerations to compression ratios less than about 10. It is evident from Fig. IV-3 that substantial improvements in ideal cycle performance could be achieved if this limiting compression ratio could be increased.

b. Actual Performance. Substantial deviations from the ideal performance occur in an actual engine. These degrade both the specific fuel consumption and the specific output from those achievable in ideal losses. The major sources of such losses are:

1. The working fluid is a mixture of air, fuel vapor, and combustion products at various points in the cycle, rather than a gas with constant specific heats, and thermodynamic losses occur due to energy retained in internal degrees of freedom of the mixture.

2. Time is required for combustion, and thus it does not take place at constant volume, resulting in a loss of potential power output.
3. Heat is transferred to and from the gas at various points in the cycle.
4. Time is required to reduce the pressure at the end of the expansion process, resulting in a further loss of potential power output.
5. Power is absorbed by friction and valving losses, which result from the gas flow and relative motion of solid surfaces necessary to implement the cycle.

Estimates of these losses, in the form of efficiency decrements ($\Delta\eta = P_{loss}/P_{add}$, where P_{loss} is the resulting loss in power output) are developed in Appendix C. The resulting impact of the losses on the best performance of Otto engines is shown in Fig. IV-5. Current Otto engines operate with a compression ratio of about 9, and achieve a minimum sfc of about 0.49, which is consistent with the results shown. It can be observed that real gas losses and frictional losses are the dominant mechanisms.

Of more significance to the present investigation is the sfc at a representative 25% power condition, selected here at 70% of maximum speed for purposes of allowing reasonable acceleration capability. In current, carbureted Otto engines, operation at part power requires reducing the inlet pressure to the engine ("throttling") to maintain the equivalence ratio at a value high enough (≥0.8) for satisfactory combustion. Part-power operation thus produces an additional throttling loss, as well as changing the magnitudes of the basic loss mechanisms. The impact of these losses on part-power sfc is shown in Fig. IV-6. (It should be noted that the presentation in Fig. IV-6 is somewhat misleading in that the relative impacts on specific fuel consumption depend upon the order in which they are shown; the impact of the losses shown in the lower portions of the figure are relatively somewhat greater than those in the higher portions.)

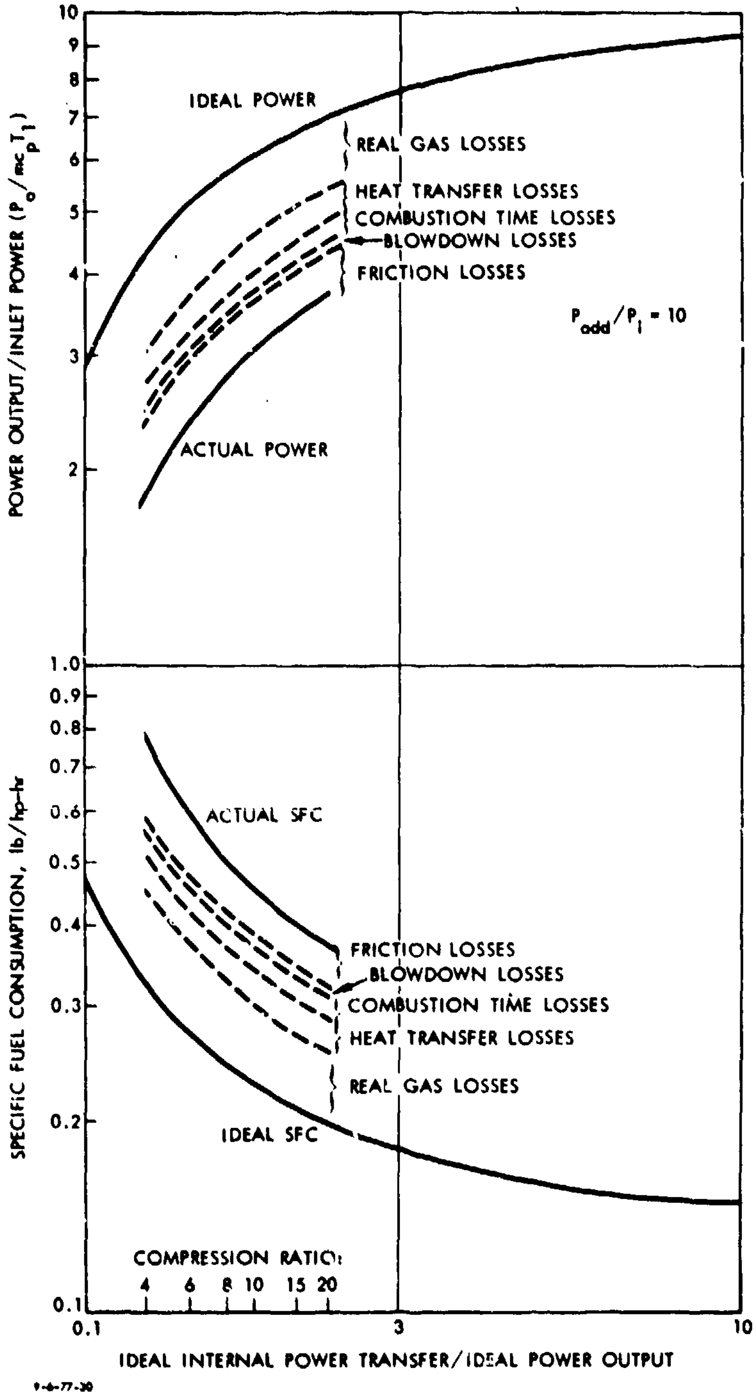

FIGURE IV-5. Impact of losses on best performance of Otto engines.

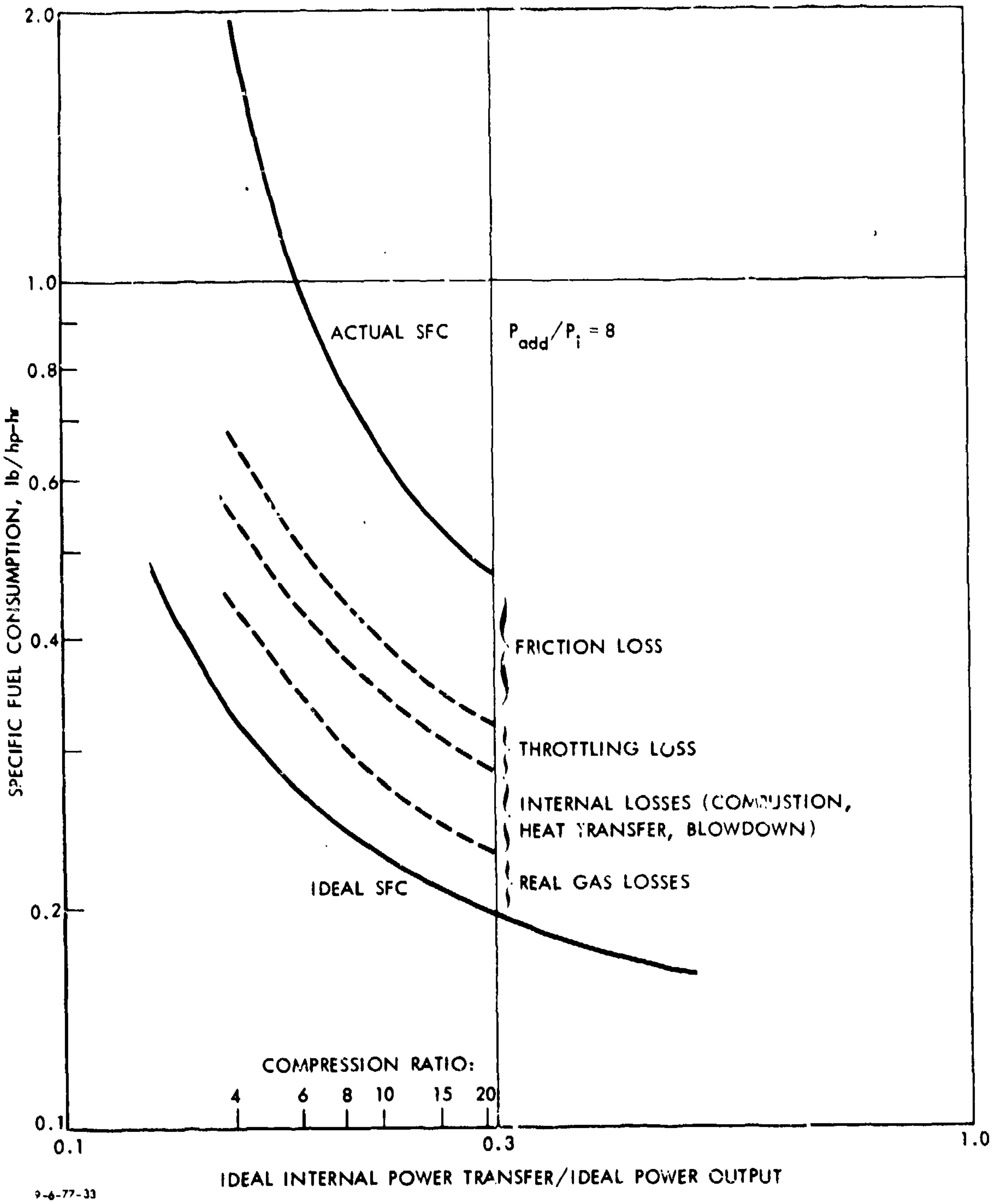

FIGURE IV-6. Impact of losses on representative part-power performance of Otto engines.

It is apparent from Fig. IV-6 that increases in internal power transfer (or compression ratio in the ideal cycle) would improve the actual performance of Otto engines, as well as the ideal performance. The losses, however, represent a large potential target for further improvement; typical current Otto engines at compression ratios in the range of 8-10 operate with an ideal specific fuel consumption of about 0.235 (58% thermal efficiency) and an actual specific fuel consumption of about 0.7 (20% thermal efficiency). It can be deduced from Fig. IV-6 that real gas effects and friction are the largest impediments to further improvement. As will be discussed subsequently, some further improvement is conceivable; first, however, it is appropriate to examine the relationship between this performance and the size and weight of engines.

c. Weight, Size, and Performance Relationships. It is convenient at the outset to distinguish among three types of weight, size, and performance relationships: (1) those associated with changes in power level; (2) those associated with changes in design choice (e.g., changes in possible compression ratios, degree of turbocharging); and (3) those associated with changes in technology (e.g., higher compression ratios, improved materials). The first type of relationship tends to be independent of both the state of technology and design choice; the second defines a state-of-the-art sfc_e-sw_e-sv_e relationship; and the third indicates the impact of improved technology.

Power scaling in an Otto engine is determined by the necessity to maintain a constant piston speed in order to maintain the same relative velocities of both mechanical parts and gas flows, and the observation that weight per unit piston displacement tends to be independent of power level. This leads to scaling laws of the form

$$\frac{W}{P_o} \sim \left(\frac{P_o}{N_{cyl}}\right)^{1/2} \sim \left(\frac{V_D}{N_{cyl}}\right)^{1/2}$$

$$N \sim \left(\frac{N_{cyl}}{V_D}\right)^{1/3}$$

where W is the engine weight, P_o the output power, V_D the piston displacement, N_{cyl} the number of cylinders, and N the rotational speed. Thus, the specific weight (and volume) scales as the square root of power for a constant number of cylinders; for a constant cylinder size, it is independent of power level. These scaling laws clearly dictate an upper limit on the power level at which an Otto engine is likely to be useful, inasmuch as there is a practical limit to the number of cylinders which can be used. Generally speaking, this appears to be less than 1000 hp. Hereafter, attention will be devoted to engines in the nominal state-of-the-art range of 45 in^3 displacement/cylinder, 20 hp/cylinder (non-turbocharged), 3600 rpm, with the understanding that the preceding scaling laws can be used for other power levels.

At a given power level, the sfc_e-sw_e-sv_e relationship for Otto engines can be thought of as being determined by the weight and volume required to accomplish the internal power transfer in the working fluid as a function of the loss incurred; plus any additional weight and volume (as a function of loss) required to withstand the peak pressures associated with combustion, to extract the power, and to provide necessary auxiliaries (primarily cooling). Obviously, many design choices, within a given state of technology, are possible: variations in internal power transfer level (compression ratio), degree of turbocharging, tradeoffs between loss and weight/volume characteristics necessary to accomplish the various functions, to name some possibilities. Ideally, it would seem desirable to associate weights,

sizes, and losses with the various functions (compression, expansion, heat addition) to be performed, in order that the nature of these design choices can be displayed explicitly. Unfortunately, the nature of an Otto engine does not lend itself to a convenient breakdown of this sort. Accordingly, the present investigation is limited to an examination of the weight breakdown of current Otto engines, the loss-weight relationship associated with the internal power transfer in Otto engines, and in a more integrated sense, the sfc_e-sw_e-sv_e relationship implied by different design choices of compression ratio and degree of turbocharging.

The current state of the art in automotive-type, reciprocating Otto engines is a specific weight of about 4 lb/hp, a specific volume of about 0.12 ft^3/hp, a part-power sfc of about 0.7, a weight per unit displacement of 1.8 lb/in^3, and a compression ratio in the region of 8-10. For aircraft engines, specific weights and volumes are about 1/2 and 3/4, respectively, of those of automotive engines, primarily as a result of the use of lighter materials and turbocharging. For automotive engines, a typical weight breakdown would be as follows:

Weight Group	Percentage	Weight/Output Horsepower (lb/hp)
Block	32	1.3
Cylinder Heads	22	0.9
Rotating Mass	24	1.0
Radiator	11	0.4
Accessories	11	0.4

A major element of the weight and loss of an Otto engine is associated with the compression (and the corresponding expansion) process. Based upon the assumptions that 2/3 of the weight associated with the block, cylinder heads, and rotating mass and all of the frictional losses are associated with this

process, a weight-loss relationship is developed in Appendix C. The indications are that in current Otto engines, the weight per unit internal power transfer is about 4 lb/hp, the loss is about 60% of the internal power transfer, and the weight scales inversely as the 3/2 power of the loss and, because reciprocating machines are essentially volume-flow devices, inversely as the inlet density at constant cylinder displacement. It is believed that this relationship is a useful benchmark for comparison with future proposed improvements in these processes, and as will be seen subsequently, it is useful for comparison with other types of power transfer equipment used in heat engines. It is also worth mentioning that power transfer by reciprocating machinery requires relatively large weight.

In a more integrated way, the sfc_e-sw_e-sv_e relationship which results from different design choices in compression ratio and degree of turbocharging is developed in Appendix C by observing that, with respect to size and weight, compression ratio affects both the peak cylinder pressure and the displacement required to produce a given power, while turbocharging (at a constant overall compression ratio) affects only the latter. Obviously, the weights of all components of an engine are not affected equally by such changes, and three different groups are identified: (1) those components which are basically unaffected by changes in peak cylinder pressure or displacement at constant power output (e.g., the accessories and the cooling system); (2) those components which are affected only through changes in displacement required to produce a given power (e.g., lowly stressed portions of the block); and (3) those components which are affected by both changes in displacement and changes in peak cylinder pressure (e.g., pistons, cylinder heads, cylinder walls). By assuming that weight per unit displacement of those components which depend on both displacement and peak cylinder pressure vary linearly with the latter, and that the displacement varies inversely as the inlet density, it is a straightforward matter

to determine the variation of specific weight and volume with variations in compression ratio and degree of turbocharging. Similarly, the impact of these changes on specific fuel consumption can be determined by assessing their effect on the ideal sfc and the various losses; the most notable of the latter is the assumption that the frictional losses vary inversely with the inlet density.

The resulting sfc_e-sw_e relationships, based upon current state-of-the-art engines, are shown in Fig. IV-7. It can be observed that turbocharging, at constant overall compression ratio, has little effect on the automotive relationship for minimum sfc, indicating that the loss in efficiency due to turbocharging is essentially identical to that obtained by decreasing the compression ratio. At part power, turbocharging improves the sfc due to a reduction in throttling required. The present state of the art is limited to compression ratios of about 10, and hence the lower portions of the curves in actuality represent improvements in the state of the art. It is to be emphasized, of course, that uncertainties exist in these relationships, particularly with regard to the dependence of the losses. However, as can be deduced from the nature of the sfc_e-sw_e-sv_e goals discussed in the previous section, great accuracy is not required for the purposes here.

d. Potential Limits for Otto Engines. From the previous development, it may be observed that the major impediments to further improvement in Otto engines include the following:

1. Limited internal power transfer (compression ratio), due to knocking. This can be alleviated by stratified-charge operation.
2. Real gas losses, which can be alleviated somewhat by lean operation in a stratified-charge engine.
3. Throttling and friction losses at representative part-power conditions, which can be alleviated by stratified-charge operation and, to some extent, by turbocharging.

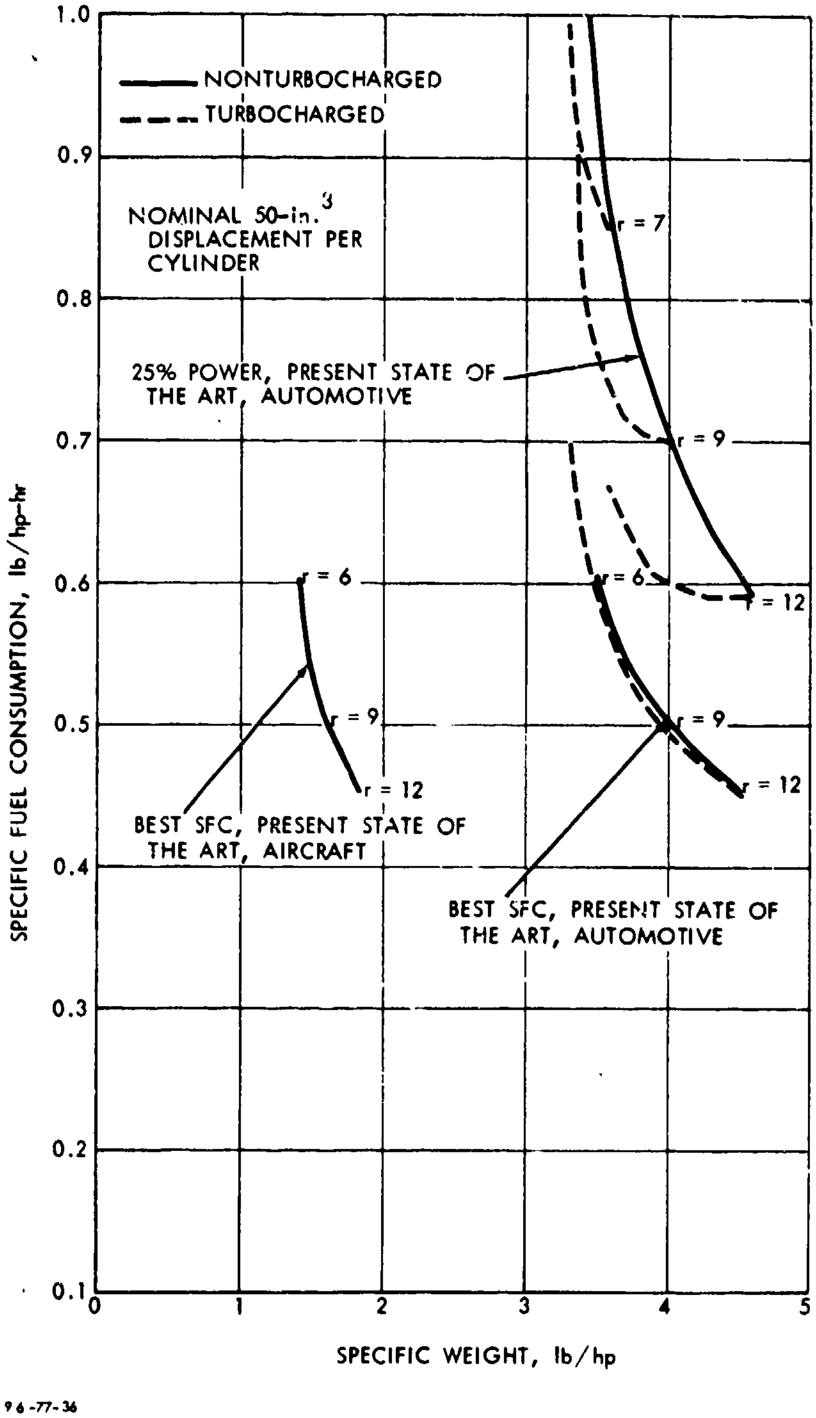

FIGURE IV-7. Specific fuel consumption--specific weight relationships for four-stroke Otto engines.

4. Heat transfer losses, which can be reduced by adiabatic operation if suitable materials can be developed.
5. The weight and size associated with limited volume-flow capabilities of reciprocating machinery, which can be alleviated by lightweight materials, turbocharging, and/or the rotary engine process.

To implement the cited potential improvements, at the same time circumventing other penalties associated with the improvement mechanisms, a "limit" engine can be postulated which, in reciprocating form, consists of:

1. Stratified-charge operation at part power and carbureted operation in the vicinity of maximum power.
2. Turbocharged operation at higher power levels, with variable compression ratio to permit maximum values at part power.
3. Adiabatic operation.
4. Use of lightweight materials.

Based on this type of an engine, it seems not unreasonable that:

1. Compression ratios up to 12 might be possible.
2. Operation at equivalence ratios down to the vicinity of 0.3 and with rapid combustion might be possible, thereby eliminating throttling losses and reducing real gas losses by about 40%.
3. The losses presently associated with heat transfer, combustion time, and exhaust blowdown could be reduced by about 1/3.
4. The specific weight for automotive-type engines would be reduced to about 2/3 that of current aircraft engines by widespread use of ceramics or other suitable lightweight material.

Use of the previously developed loss relationships and scaling laws then permits an estimate of the sfc_e-sw_e characteristics to be made, with the results shown in Fig. IV-8. The engine specific

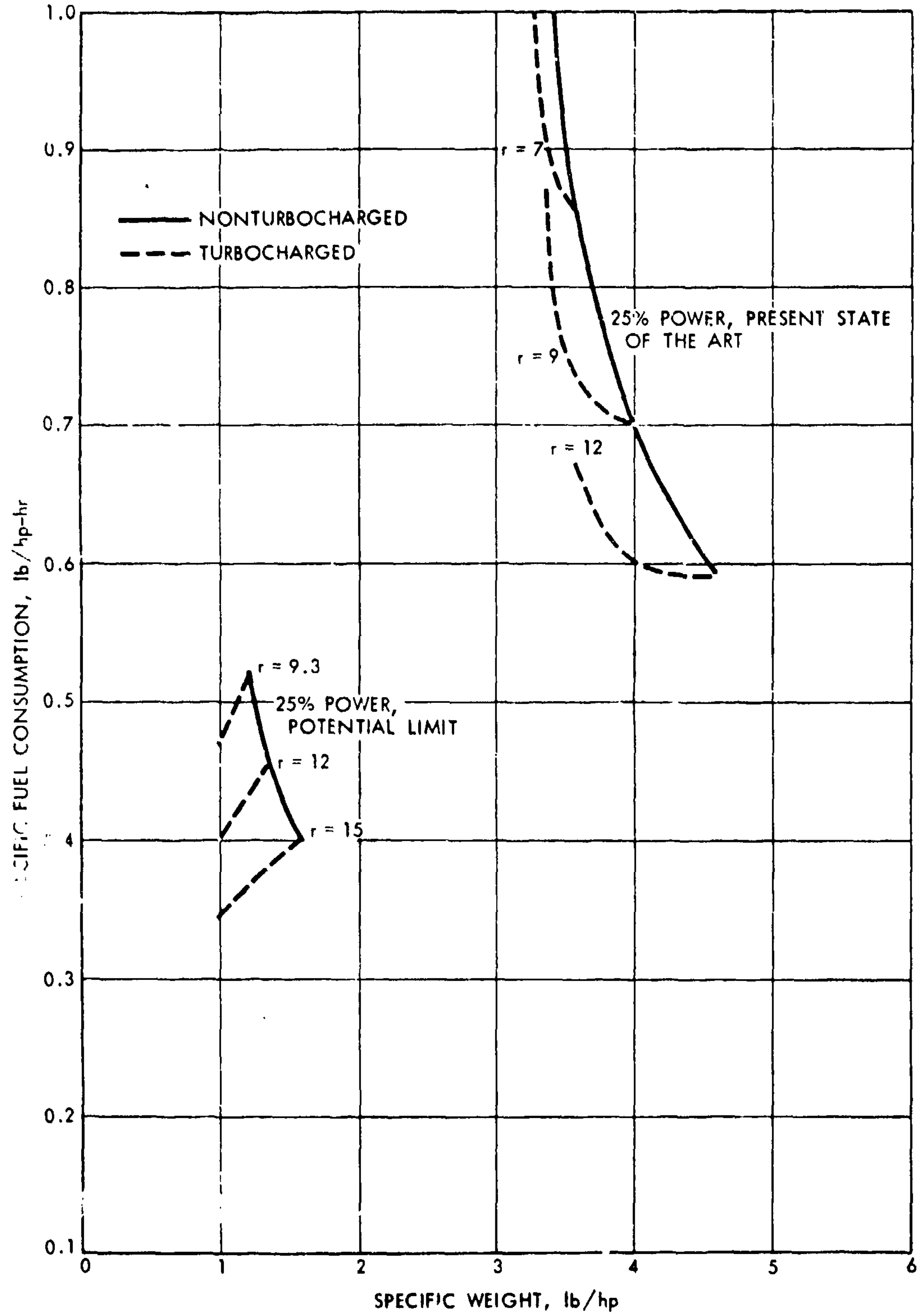

FIGURE IV-8. Spec : fuel consumption--specific weight limits for .r-stroke Otto engines.

volume is estimated to be that obtained from a density of about 15 lb/ft^3. Consistent with the compression ratio limit of 12, the lower part of the curve is not expected to be possible at all. This limit is of course always subject to both revision and misinterpretation. The interpretation here is that performance of Otto engines cannot reasonably be expected to exceed this limit in the foreseeable future; whether an Otto engine can indeed approach this limit depends upon whether the problems associated with stratified-charge, lean, variable-compression-ratio operation, rapid combustion, no heat transfer losses, and use of lightweight materials can be simultaneously solved successfully. It is to be emphasized that currently no such simultaneous solutions are evident.

No corresponding estimate has been made here for the rotary engines, since the losses are somewhat difficult to quantify. It seems reasonable to expect the specific weight limit to be slightly less than 50% of that of the reciprocating Otto, but with a somewhat higher specific fuel consumption.

e. Suitable Goals and High-Payoff Areas for Otto Engines. In the context of this report, no suitable goals are offered for Otto engines in the combat-vehicle applications studied here. Although the estimate of the potential limit of Otto engines indicates that large improvements may still be possible, they do not result in a sufficiently large impact on the vehicles considered.

The technology areas with the highest payoff in improving Otto engine performance, for perhaps other applications, appear to be as follows (in priority order):

1. Stratified-charge, lean operation at part power, in combination with variable-compression-ratio operation and carburetion at full power, with all of the injection, combustion, and mechanical problems that this implies. The estimate here is that as much as a 30% reduction in part-power sfc might be possible.

2. Lightweight materials of construction, if such can be developed. It is estimated that a factor-of-2 reduction in specific weight might be possible.
3. High-temperature materials which permit adiabatic operation. It is estimated that an additional 20% reduction in specific weight and 10% reduction in part-power sfc might be possible.

3. Diesel Engines

a. **Ideal Performance**. The conventional diesel cycle is generally idealized in two forms: the constant-pressure cycle and the limited-pressure cycle. The constant-pressure (cp) cycle consists of isentropic compression, combustion at constant pressure, isentropic expansion, and heat rejection at constant volume. The limited-pressure (lp) cycle is identical to the constant-pressure cycle, except that combustion occurs partially at constant volume and partially at constant pressure. Thus, the two limits of the lp cycle are the Otto and cp Diesel cycles. For a given fuel, the basic cycle parameters are the compression ratio, the fuel-air ratio, and (for lp cycles) the pressure ratio attained during constant-volume combustion. The internal power transfer is that required for compression, the power added is the heat-release rate during combustion, and the power output is the difference between the power developed during expansion and that required for compression. The ideal performances of both cp and lp cycles are shown in Fig IV-9, where r_{cv} denotes the pressure ratio achieved during constant-volume combustion. It is to be noted that values of the parameter $\gamma P_{add}/P_1$ of 10 and 3 correspond to equivalence ratios of approximately 0.77 and 0.23, respectively, and roughly span the range encountered in current diesel engine operation. It can be observed that improvements in ideal specific fuel consumption require large increases in compression ratio. The effect of limited-pressure operation is to reduce the internal power transfer (and compression ratio) required for a given ideal performance, such that the ideal

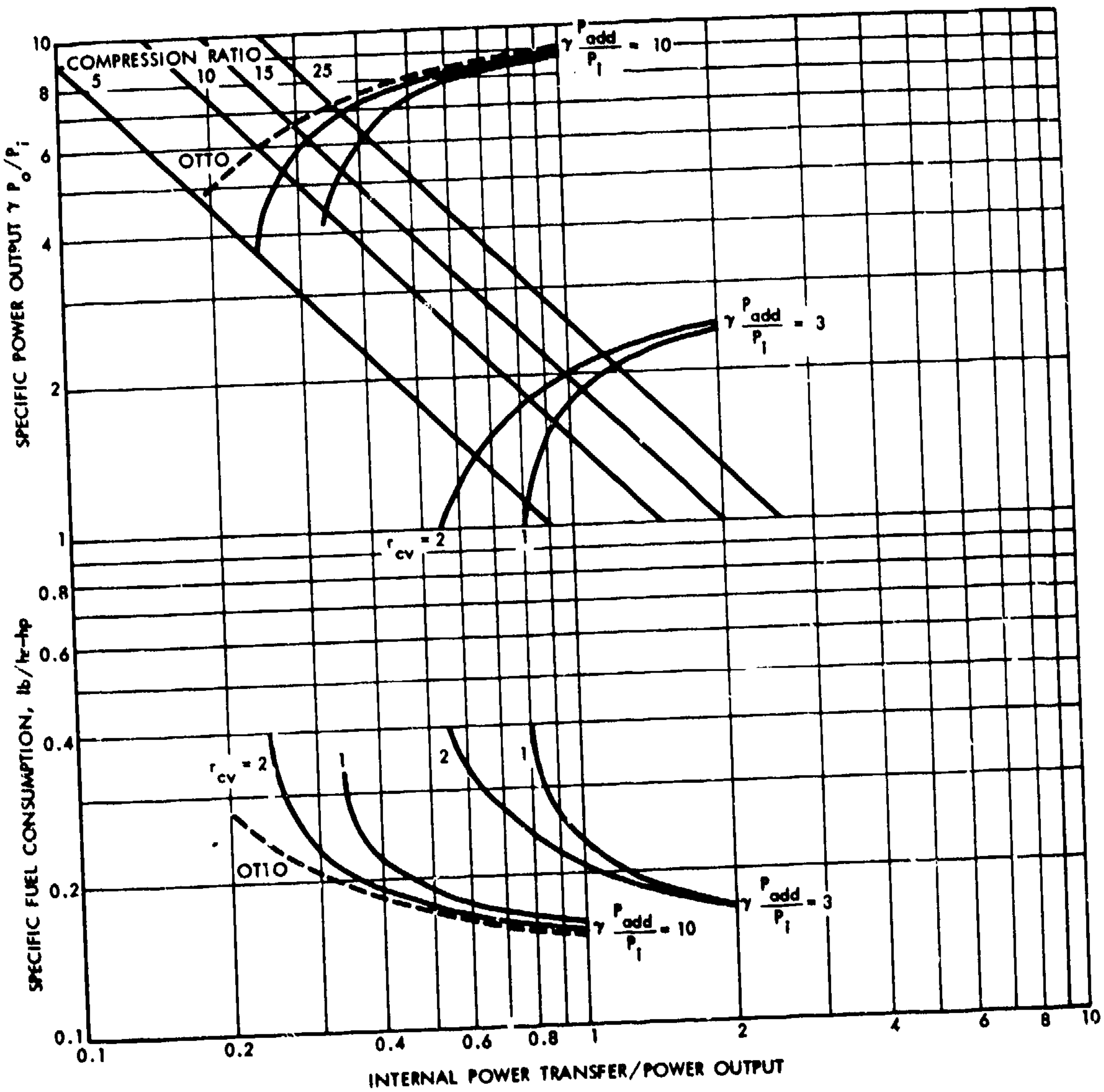

FIGURE IV-9. Performance characteristics of the ideal-gas, standard Diesel cycle.

performance eventually approaches that of the Otto cycle. As it happens, toward the constant-pressure end of the spectrum, the ideal performance depends only upon the peak cylinder pressure. For simplicity, the analysis here will be devoted primarily to cp diesel cycles, with the understanding that, in actual practice, the operation may be of the limited-pressure type, at somewhat lower compression ratios.

As with the Otto cycle, a major source of thermodynamic inefficiency in the ideal diesel cycle is in the relatively high available energy content of the exhaust gases, and a major source of weight and size is due to the limited volume-flow capability of reciprocating machinery. Three variations of diesel cycle to alleviate these difficulties are examined in Appendix D: the supercharged diesel cycle, the turbocharged diesel cycle, and the compound diesel cycle. The effects of supercharging or turbocharging on ideal performance are similar, and are similar to the effects of turbocharging on an Otto cycle: an increased inlet density at the expense of increased sfc and decreased specific power output.

The compound diesel cycle consists, in the limit, of expanding the gas in the cylinder at the end of the expansion stroke through a turbine to ambient pressure, and extracting useful power output from the turbine. In general, this compounding will increase the power input to the piston during the exhaust stroke, which detracts from the net power output. Compounding can also be used in conjunction with a supercharger, in which case the basic cycle parameters can be taken to be the overall compression ratio, the fuel-air ratio, and the fraction of total compression power devoted to the supercharger. The ideal performance of this cycle is shown in Fig. IV-10, where it is to be noted that the total internal power transfer includes both that to the supercharger and that required by the piston during the exhaust stroke. It can be observed that the compound diesel does not offer any advantage in terms of performance at

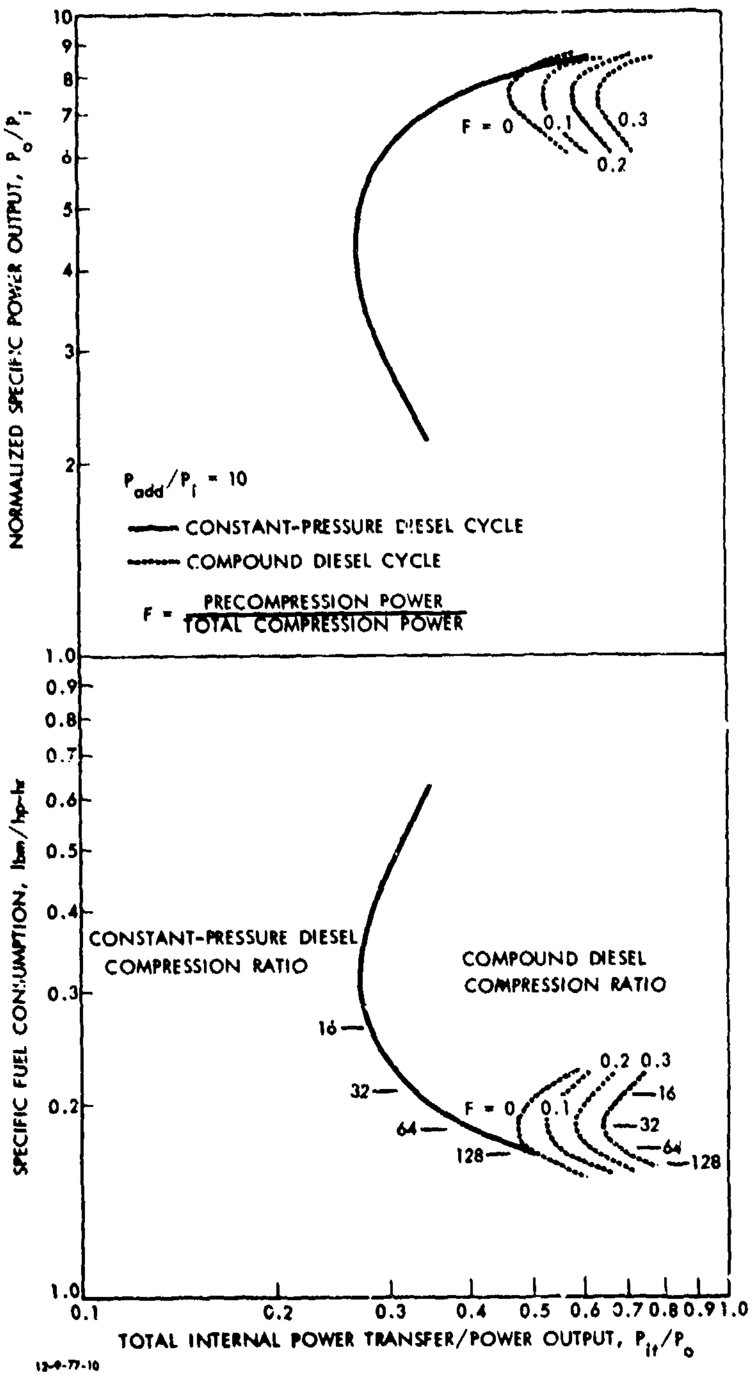

FIGURE IV-10. Performance characteristics of the ideal compound-Diesel cycle.

a given level of internal power transfer; it does, however, reduce the compression ratio required to achieve the necessary power transfer, as well as utilize rotating machinery to accomplish part of the power transfer and power extraction.

With respect to further improvements in the ideal performance of diesel engines, present engines operate at maximum equivalence ratios in the range of 0.8 to 0.9, and thus some improvement in specific heat addition could be achieved by successful operation with stoichiometric mixtures. As with the Otto engine, however, additional significant improvements must originate in increasing the ratio of internal power transfer to power output. The compound diesel, in principle, provides the means for such an increase without an exorbitant increase in the required compression ratio.

b. <u>Actual Performance</u>. The major sources of losses in a diesel engine are similar to those in Otto engines:

1. The real gas losses associated with energy retained in the internal degrees of freedom of the working-fluid mixture.
2. Combustion losses associated with the finite and variable rate of heat release.
3. Heat transfer losses.
4. Friction and valving losses.

Estimates of these losses are developed in Appendix D. The resulting impact of these losses on the minimum specific fuel consumption of diesel engines is shown in Fig. IV-11. Current diesel engines are generally of the lp type, operating at compression ratios of 15-20 and peak cylinder pressures of 2000 psia (which is roughly equivalent, thermodynamically, to a cp diesel with a compression ratio of about 35), and achieve a minimum sfc of about 0.34. Thus, the loss estimates in Appendix D are evidently somewhat low. Nevertheless, the results do indicate the importance of real gas losses in determining the actual

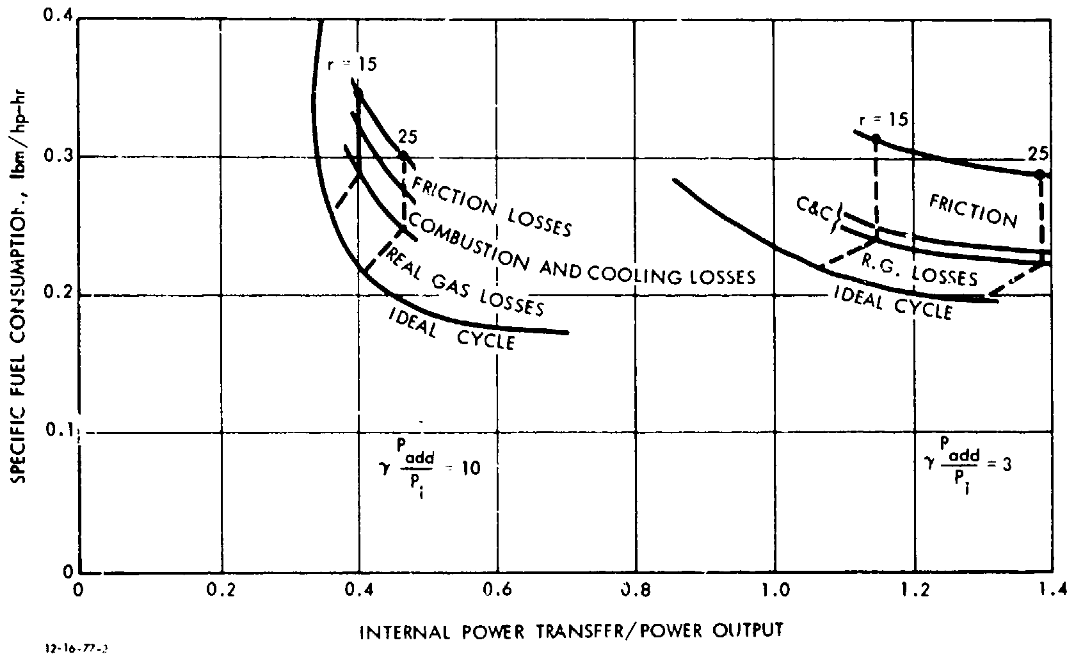

FIGURE IV-11. Impact of losses on specific fuel consumption of standard, constant-pressure (r_{cv} = 1). Diesel cycle.

performance of diesel engines at high loads (i.e., $\gamma P_i/P_{add} \approx 10$) and the importance of frictional losses at low loads (i.e., $\gamma P_i/P_{add} \approx 3$).

The major interest here is of course the actual performance at a representative 25% power condition. Unlike Otto engines, diesel engines operate unthrottled at lower equivalence ratios at part power, with the result that the sfc is less dependent on the power and speed levels than in the Otto. The individual loss magnitudes do change, however, since real gas losses decrease with decreasing equivalence ratio, combustion losses decrease with decreasing speed, heat transfer losses decrease with decreasing equivalence ratio and increasing speed, and friction losses increase with increasing speed and decreasing equivalence ratio. Taking 25% power and 70% speed as the representative part-power condition, a slightly revised estimate of the individual losses* indicates an sfc of about 0.42 at an

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*For the record, since it is not contained in Appendix D, the part-power performance is estimated by:

$$\eta = (\eta_{id} - 0.09\phi) - 0.12(\eta_{id,o} - 0.09\phi)$$

$$- 0.07(\eta_{id,o} - 0.09\phi)(p/p_{ref})(\rho_{ref}/\rho)(r/32)^{0.4}$$

$$- 0.22(\rho_{ref}/\rho)(\eta_{id,o} - 0.09\phi) ,$$

where η_{id} is the ideal efficiency, $\eta_{id,o}$ is the ideal efficiency in the absence of supercharging, p_{ref} and ρ_{ref} are the ambient pressure and density, and p and ρ are the pressure and density after any supercharging. The term 0.09ϕ represents real gas losses, the second term above represents combustion losses, the third term represents heat transfer losses, and the last term represents frictional losses. It is assumed that this relationship is an estimate of efficiency at maximum power conditions, and that the part-power efficiency is 5% less than this value. This yields reasonable agreement with current diesel engines, although the individual losses at part power are relatively different than at full power: frictional losses are relatively greater and the other losses are relatively less.

equivalent cp compression ratio of 32, which is in reasonable agreement with current diesel engine performance. At these conditions, the losses are dominated by friction.

From either Fig. IV-11 or this estimate of part-power performance, it can be observed that increases in internal power transfer (or compression ratio) would improve both the ideal performance and the actual performance of diesel engines. As with the Otto engine, however, the losses represent large potential targets for improvement; current engines operate with an ideal sfc of approximately 0.21 (66% thermal efficiency), but an actual sfc of about 0.4 (35% thermal efficiency). Of the various loss mechanisms, friction appears to be the largest impediment to improvement in part-power performance.

c. **Weight, Size, and Performance Relationships**. The nature of weight, size, and performance relationships for diesel engines is completely analogous to those for Otto engines, and they are treated in the same manner here (with the same attributes and deficiencies).

Power scaling--for fixed technology and design choices--for specific weight and rotational speed is approximately

$$\frac{W}{P_o} \sim \left(\frac{P_o}{N_{cyl}}\right)^{1/2} \sim \left(\frac{V_D}{N_{cyl}}\right)^{1/2}$$

and

$$N \sim \left(\frac{N_{cyl}}{V_D}\right)^{1/3} .$$

Again, an upper limit in the power level at which a diesel can be competitive in specific weight (or volume) is indicated. This appears to be in the range of 2000-2500 hp for the applications considered here. Hereafter, attention will be largely devoted to engines in the nominal range of 100 in^3 displacement

per cylinder, 50 hp/cylinder (non-supercharged), and 2600-2800 rpm, with the understanding that these scaling laws can be used for other power levels.

At a given power level, the sfc_e-sw_e-sv_e relationship is determined by a spectrum of design choices offered by trade-offs within the weight-size-loss relationships associated with accomplishing the necessary power transfers. As with the Otto engine, the size and weight of components of a diesel engine cannot easily be related to individual power transfer functions with the exceptions of those associated with reciprocating compression, which is identical to that of the Otto, and rotating compression, which is identical to that of turbine engines, as will be discussed subsequently. Therefore, the same integral approach, based on weight breakdowns of current engines, as used for Otto engines will be used here for developing the sfc_e-sw_e-sv_e relationships. Similarly, only the design choices of compression ratio and degree of turbocharging are examined here.

The current state-of-the-art in automotive-type diesel engines is exemplified by an air-cooled, variable compression ratio, highly turbocharged (a turbocharging pressure ratio of about 4), aftercooled engine, with a specific weight slightly greater than 3 lb/hp, a specific volume of about 0.06 cu ft/hp, a part-power sfc of about 0.4, a weight per unit displacement of about 3 lb/in^3, and a peak cylinder pressure of about 2000 psia (corresponding to an equivalent cp diesel with an overall compression ratio of about 32). By convention, these values are referred to gross horsepower output, about 11% of which is required for air cooling. For aircraft diesels (which have now passed out of existence), specific weights were in the range of 1.5 to 2.0 lb/hp, presumably due to the use of lighter materials at some sacrifice in life. For current automotive-type engines, a typical weight breakdown would be as follows:

Weight Group	Percentage	Weight/Output Horsepower (lb/hp)
Block & Heads	28	0.86
Rotating Mass	19	0.58
Induction/Exhaust	3	0.08
Turbocharging & Aftercooling	12	0.38
Air Cooling	13	0.39
Lubrication	10	0.32
Fuel Injection	7	0.22
Accessories	8	0.26

In terms of power actually transferred, the weights associated with turbocharging and aftercooling are estimated to be about 0.43 lb/hp for each function.

The sfc_e-sw_e-sv_e relationships which result from different design choices and compression ratio and degree of turbocharging can be developed in a way analogous to that for Otto engines. Qualitatively, different compression ratios affect (1) the peak cylinder pressure and hence the weight and size of some portion of the engine, (2) the ideal performance through changes in internal power transfer, and (3) the losses, particularly those due to heat transfer. Different amounts of turbocharging (at constant overall compression ratio) affect (1) the volume flow into the reciprocating portion and hence the weight and size, (2) the ideal performance, and (3) the losses, particularly those due to friction. Four groups of components affected differently by such changes can be identified: (1) components affected only by changes in power level; (2) components affected by the displacement required to produce a given power; (3) components affected by both the displacement and peak pressure required to produce a given power; and (4) the turbocharging and aftercooling components. By assuming that the weight per unit displacement of those components which depend upon both displacement and peak cylinder pressure varies linearly with

the latter, that the displacement varies inversely as the inlet density, and that weight per unit power transferred by turbochargers and aftercoolers is constant, the variations in specific weight and volume with changes in compression ratio and amount of turbocharging can be determined in a straightforward way. Similarly, the impact of such changes on specific fuel consumption can be determined by assessing their effect on the ideal sfc and the various losses.

The sfc_e-sw_e relationship, based on current state-of-the-art engines, which results is shown in Fig. IV-12, with data from three existing engines. (Potential limits for diesel engines, as discussed subsequently, are also shown in Fig. IV-120. Again, it is to be noted that the values shown are based on gross horsepower output. The low-specific-weight portion of the curve represents turbocharged engines, and the higher-specific-weight portion represents naturally aspirated (i.e., non-turbocharged) engines.

d. Potential Limits for Diesel Engines. Based upon the previous development, the major impediments to further improvements in diesel engines appear to be the following:

1. Limited internal power transfer due to the excessive compression ratios and high cylinder pressures required. This can be alleviated somewhat by the compound cycle and by improved high-temperature materials.
2. Somewhat limited specific power addition, due to inability to provide proper combustion at equivalence ratios up to unity.
3. Friction losses at part-power conditions, which can be alleviated somewhat by high turbocharging.
4. Heat transfer losses, which detract only modestly from cycle efficiency, but which require a significant cooling system.

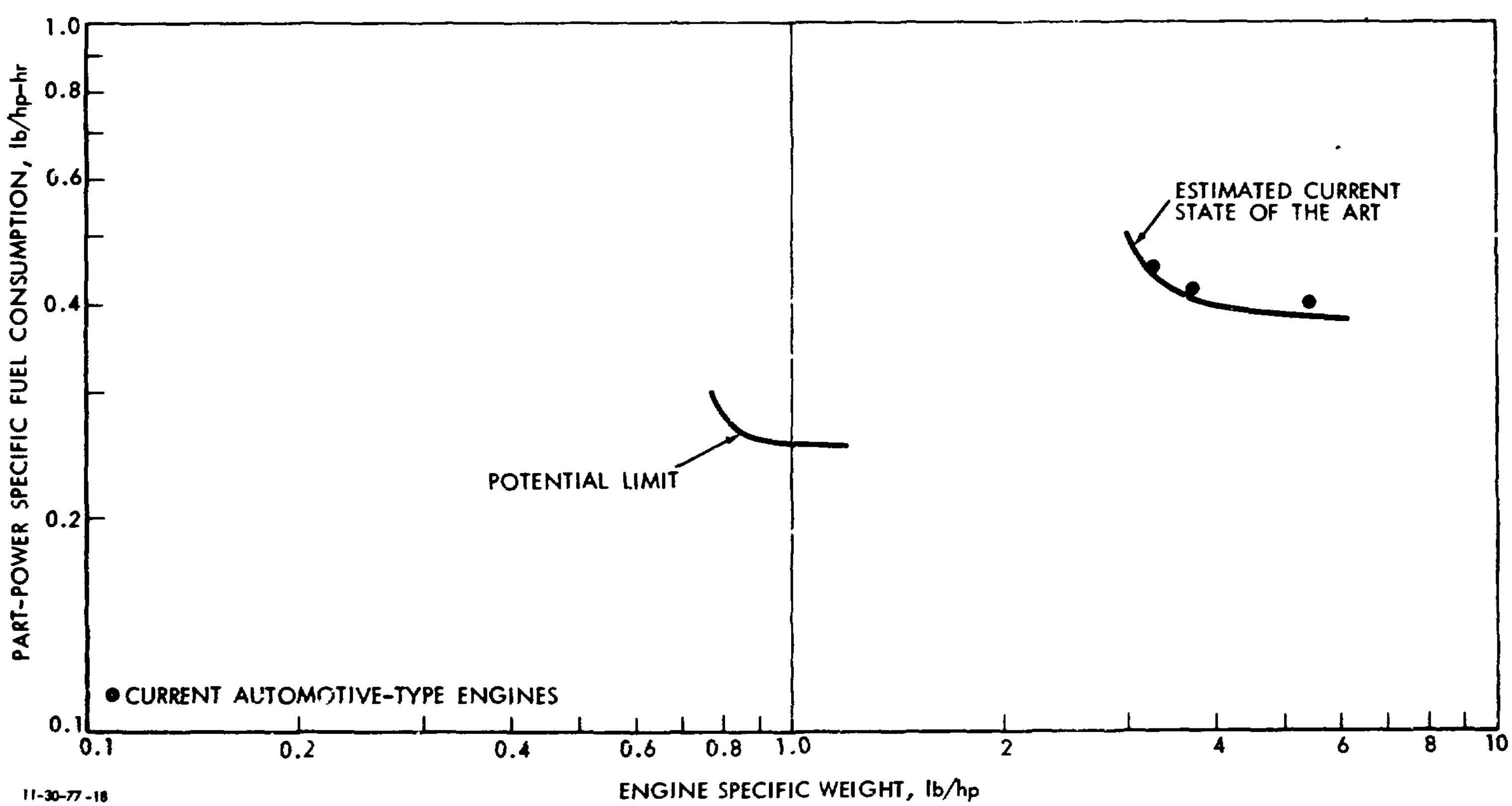

FIGURE IV-12. Specific fuel consumption--specific weight relationships for Diesel engines.

5. The weight and size associated with the limited volume-flow capabilities of reciprocating machinery, which could be alleviated somewhat by lightweight materials, more turbocharging, and higher speeds.

To overcome these obstacles, in the manners indicated, a "limit" engine can be postulated which consists of:

1. Turbocompound, turbocharged operation.
2. Improved high-temperature materials to withstand adiabatic operation and higher peak cylinder pressures.
3. Operation at equivalence ratios of unity.
4. Operation at higher rotational speeds and higher piston speeds.
5. Use of lightweight materials.

Based upon this type of an engine, it seems not impossible that:

1. Ideal sfc could be reduced from the present level of about 0.22 to 0.175, by means of compounding and higher cylinder pressures.
2. Peak cylinder pressures of 4000 psi could be attainable.
3. Heat transfer losses, as well as the cooling system, could essentially be eliminated.
4. The specific power output could be increased by an additional 10-15% by stoichiometric operation.
5. The volume-flow capacity of the reciprocating portion of the engine could be doubled (at the same weight).
6. The specific weight of current, air-cooled, highly turbocharged, automotive-type diesel engines could be reduced from the present level of about 3.1 lb/hp to about 1.5 lb/hp by the use of suitable lightweight materials (as in earlier aircraft diesels) alone.

Use of the previously developed loss relationships and scaling laws* then permits an estimate of the sfc_e-sw_e characteristics to be made, with the results as shown in the left portion of Fig. IV-12. The engine specific volume is estimated to be that obtained from a density of about 35 lb/ft^3. Again, it is to be emphasized that the interpretation of these relationships is that the performance of diesel engines cannot reasonably be expected to exceed this limit in the foreseeable future. Attaining such a limit requires the simultaneous solution of problems associated with doubling the peak cylinder pressure, compounding, extreme exhaust valve temperatures, proper combustion at stoichiometric conditions, high-temperature materials to withstand adiabatic operation, high rotational speeds, and lightweight materials.

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*Again for the record, since it is not contained in Appendix D, the specific weight is estimated from

$$\frac{W}{P_o} = \frac{W_p}{P_o} + \left(\frac{W_D}{V_D}\right)\left(\frac{V_D}{\dot{V}}\right)\left(\frac{\rho_{ref}}{\rho}\right)\left(\frac{\gamma-1}{\gamma}\right)\left(\frac{P_o}{P_i}\right)\frac{1}{P_{ref}}$$

$$+ \left(\frac{W_{TC}}{P_{TC}}\right)\left(\frac{P_{TC}}{P_o}\right) + \left(\frac{W_{AC}}{P_{AC}}\right)\left(\frac{P_{AC}}{P_o}\right) + \left(\frac{W_T}{P_T}\right)\left(\frac{P_T}{P_o}\right)$$

where W_p is the portion of engine weight which depends only upon power (W_p/P_o is taken as 0.50 lb/hp), W_D is that portion of engine weight which depends upon displacement and peak pressure (W_D/V_D is taken as 0.70 lb/in^3 displacement at 4000-psi cylinder pressure), $V_D/\dot{V}$ is the displacement required per inlet volume flow (taken as 0.027 seconds), W_{TC}/P_{TC} is the weight per unit power transfer associated with turbocharging (taken as 0.30 lb/hp), P_{TC}/P_o is the turbocharger power per unit output power (a cycle parameter), W_{AC}/P_{AC} is the weight per unit power transfer associated with aftercooling (taken as 0.50 lb/hp for a high-effectiveness aftercooler), P_{AC}/P_o is the ratio of aftercooler power transfer to output power (a cycle variable), W_T/P_T is the weight per unit power transfer associated with the compound turbine (taken as 0.10 lb/hp, including gearing), and P_T/P_o is the ratio of the compound-turbine power to the output power (a cycle parameter).

It is instructive to look at the origins of this limiting performance in terms of individual gains due to changes in the ideal cycle, improvements in the losses, and improvements in specific weight of the components. Taking a typical point on the state-of-the-art curve in Fig. IV-12 as an sfc_e of 0.45 (31% thermal efficiency) and a specific weight of 3.15 lb/hp, and a typical point on the potential curve as an sfc_e of 0.26 (53% thermal efficiency) and a specific weight of 0.82 lb/hp, then the total changes amount to an efficiency gain of 22 percentage points and a change in specific weight of 2.33 lb/hp. It is estimated that the ideal cycle performance correspondingly changes approximately from an sfc of 0.22 to 0.17, representing an efficiency gain of 18 percentage points, and from a specific power (P_o/P_1) of 5 to 8. The improvements in ideal performance are primarily due to an increase in the ratio of internal power transfer to power output (P_{it}/P_o) from approximately 0.4 to 0.6, and to a lesser extent to an increase in specific power addition from 8 to 9.3. The impact of changes in losses (primarily the reduction of heat transfer losses) accounts for the other 4 percentage points in efficiency, and a change in actual specific power output (P_o/P_1) from approximately 2.6 to 5.2. Thus, the improvement in sfc is due largely to the improvement in ideal cycle performance. With respect to specific weight, it is estimated that the increase expected from increasing peak cylinder pressure is approximately offset by the increase in specific power; the decrease of 2.33 lb/hp is due largely to use of lightweight materials in the displacement-related components (0.7-1.4 lb/hp),* and elimination of the cooling system (0.25 lb/hp).* Of course all of these individual gains depend to some extent upon what representative points are selected on the two curves of Fig. IV-12; nevertheless, they do give a reasonable

*As might be expected, a single value cannot be placed on these individual reductions, since they depend upon the order in which it is assumed that the improvements are taken.

indication of the individual improvements which have the largest impact on engine performance.

e. <u>Suitable Goals and High-Payoff Technology Areas for Diesel Engines</u>. As developed in Section III, suitable goals for diesel engines for ground combat-vehicle applications are in the vicinity of a part-power sfc of 0.32 lb/hp-hr and a specific weight of 1.6 lb/hp. It can be observed from the representative current and potential-limit design points discussed above that these goals represent an improvement of about 2/3 of that which is estimated as perhaps being possible. If it is presumed that the individual constituents (ideal cycle performance, loss impact, component weight and size) of the potential-limit performance are equally difficult to attain, then one suitable set of goals would be that obtained by linear interpolation between the current state-of-the-art values and the estimated limits, as follows:

1. An ideal cycle performance of a sfc of 0.19 (73% thermal efficiency), a specific power output (P_o/P_i) of 7, and a specific power addition (P_{add}/P_o) of somewhat less than 9 (an equivalence ratio of about 0.9); this implies an ideal internal power transfer/power output ratio of about 0.55 and peak cylinder pressure of about 3300 psi.
2. A reduction in heat transfer losses to 1/3 of their present values.
3. A 1/3 reduction in the displacement required per unit volume flow (from 0.054 sec to 0.036 sec).
4. A specific weight of the displacement-related components of 0.60 $lb/in.^3$ at 3300 psi cylinder pressure (as compared to the current level of 1.6-1.7 $lb/in.^3$ at 2000 psi cylinder pressure).
5. A specific weight of the power-related components of 0.36 lb/hp (as compared to the current level of 0.8-0.9 lb/hp).

6. A specific weight of the cooling system of 0.15 lb/hp (as compared to the current level of 0.4-0.5 lb/hp).

The goals outlined above do not of course give any indication of their relative impact on engine performance, and hence no indication of the higher payoff areas. These areas are, however, evident from the previous discussion of the origins of the estimated limiting performance; in order of decreasing impact, they are:

1. Improved ideal cycle performance by increasing the internal power transfer/power output ratio; this accounts for roughly 80% of the total efficiency change estimated to be possible. The implications are that compound engines are a necessity, and that reductions in heat transfer losses are highly desirable.
2. Improved materials or design techniques for displacement-related components; of the 2.3 lb/hp specific weight reduction estimated to be perhaps possible, 0.7-1.4 lb/hp originates here.
3. Improved materials or design techniques for power-related components; a reduction of 0.55 lb/hp in specific weight is estimated to be not impossible.
4. Improved volume flow capacity of reciprocating machinery; a specific weight reduction of 0.2-0.9 lb/hp is estimated to be not impossible.

4. Open Brayton-Cycle (Gas-Turbine) Engines

a. Ideal Performance. The simple Brayton cycle consists of isentropic compression, heat addition by combustion at constant pressure, isentropic expansion, and heat rejection at constant pressure. For a given fuel, the basic cycle parameters are the compressor pressure ratio and the ratio of maximum cycle temperature (after heat addition) to the inlet temperature. The internal power transfer is that required for compression, the power added is the heat-release rate during combustion, and the power output is the difference between that developed during

expansion and that required for compression. The major variant of the simple Brayton cycle is the regenerated Brayton cycle, in which a heat exchanger is used to transfer heat from the gas at the end of expansion to the air after compression. In this cycle, the internal power transfer is both that required for compression and the rate of heat exchange.

The ideal performance of both simple (denoted by CBE) and regenerated (denoted by CBEX) cycles is developed in Appendix E and is shown in Fig. IV-13. It should be noted that the parameter $(P_{add} + P_{int})/P_i$ is one less than the ratio of maximum to minimum temperature; thus, for an inlet temperature of 60°F, a ratio of $(P_{add} + P_{int})/P_i = 5$ implies a maximum temperature of 2660°F. The sfc and specific power relationships, as functions of the internal power transfer ratio (P_{int}/P_o) and specific heat addition $[(P_{add} + P_{int})/P_o]$, are identical for both the simple and regenerated cycles; the difference in cycle performance is in the much higher pressure ratio required to achieve a given level of internal power transfer in the simple cycle. It can be observed that the ideal sfc is affected primarily by the internal power transfer ratio and that the ideal specific power is affected largely by the specific power addition (or maximum temperature).

With respect to further improvements in ideal performance, current simple-cycle gas-turbine engines operate in the vicinity of $(P_{add} + P_i)/P_{int} \approx 5$ (a maximum temperature in the range of 2500°F) and $P_{int}/P_o \approx 0.7$ (a pressure ratio of about 25). Regenerated gas turbines operate in the vicinity of $(P_{add} + P_i)/P_{int} \approx 4$ (a maximum temperature of about 2000°F) and $P_{int}/P_o \approx 2.0$ (a pressure ratio of about 4). Maximum temperatures are currently limited by materials considerations, and are ultimately limited by stoichiometric considerations to values in the range of 3500°F-4000°F [corresponding to $(P_{add} + P_{int})/P_i \approx 7$]; increases in temperatures to these values would provide significant increases in specific power output,

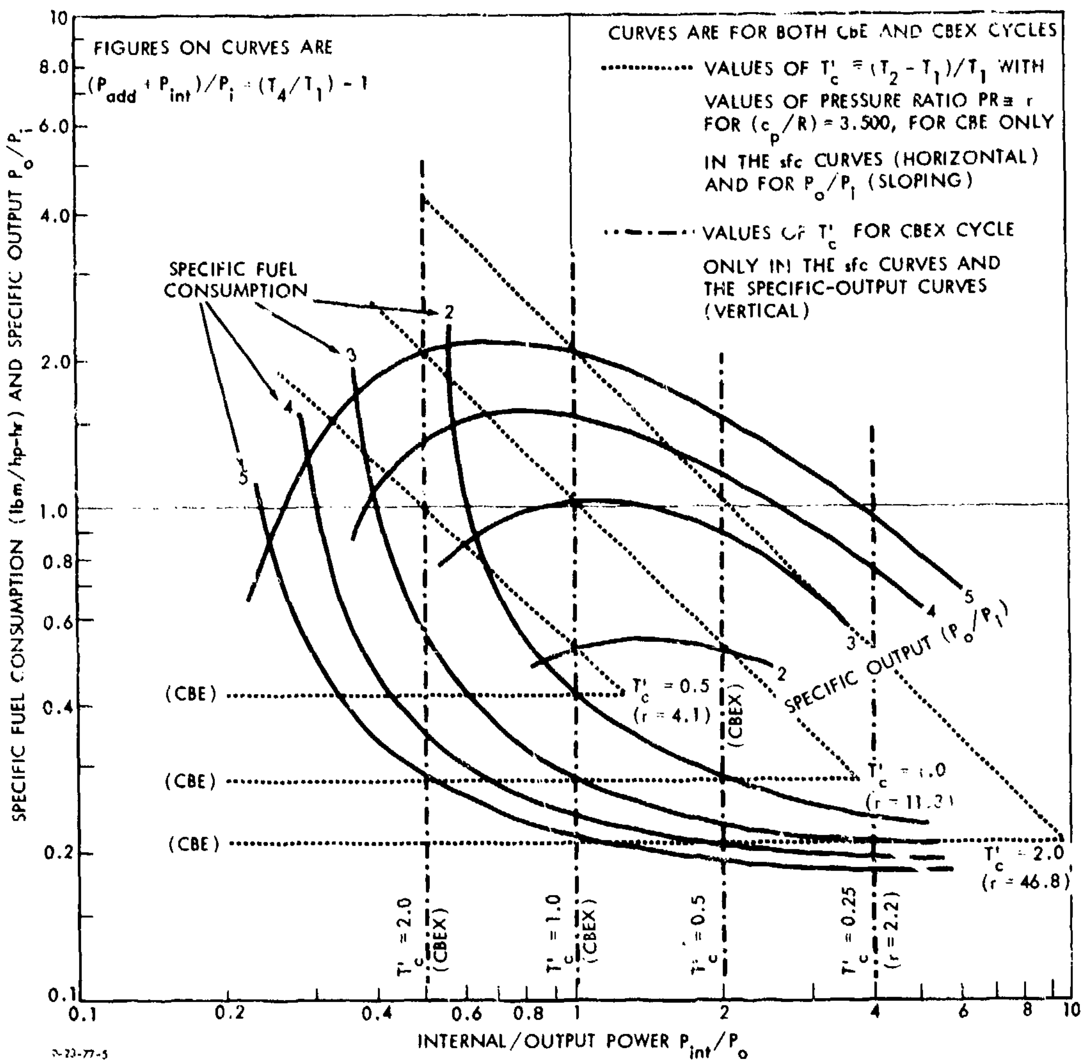

FIGURE IV-13. Performance of ideal Brayton cycles.

particularly for regenerated cycles. For simple cycles, increases in the ratio of internal power transfer/power output by means of increasing pressure ratio offers the only significant way to improve the ideal sfc; for regenerated cycles, the potential for improving the ideal sfc is quite limited.

b. Actual Performance. Unlike Otto and diesel engines, the losses in a Brayton cycle are generally easily identifiable with the power transfer processes and corresponding components. The major sources of loss are: (1) the compressor, characterized by a polytropic efficiency or an isentropic efficiency; (2) the combustor, characterized by a pressure loss and a combustion efficiency (which, for all practical purposes, is 100%); (3) the turbine, characterized by a polytropic efficiency or an isentropic efficiency; (4) the heat exchanger, in a regenerated cycle, characterized by a pressure loss and an effectiveness, defined as the ratio of heat actually transferred to the thermodynamically possible heat transfer; and (5) miscellaneous ducting losses, characterized by a pressure loss. Real gas losses are of course also present in Brayton cycles, but not to the extent found in Otto and diesel cycles; estimates indicate that real gas losses are somewhat less than 5 percentage points in efficiency in Brayton cycles, and they are not dealt with explicitly here.*

The impact of these individual losses on ideal performance is estimated in Appendix E. Representative results are shown in Fig. IV-14, for the simple-cycle, and in Fig. IV-15, for the regenerated cycle. It is to be noted that the losses assumed, although they are to some extent matters of design choice arising from tradeoffs among weight, volume, and specific fuel consumption, are reasonably close to the minimum values which

*Current engines operating at maximum temperatures above about 1900°F require air cooling of the turbine blades, which introduces another loss not explicitly considered here.

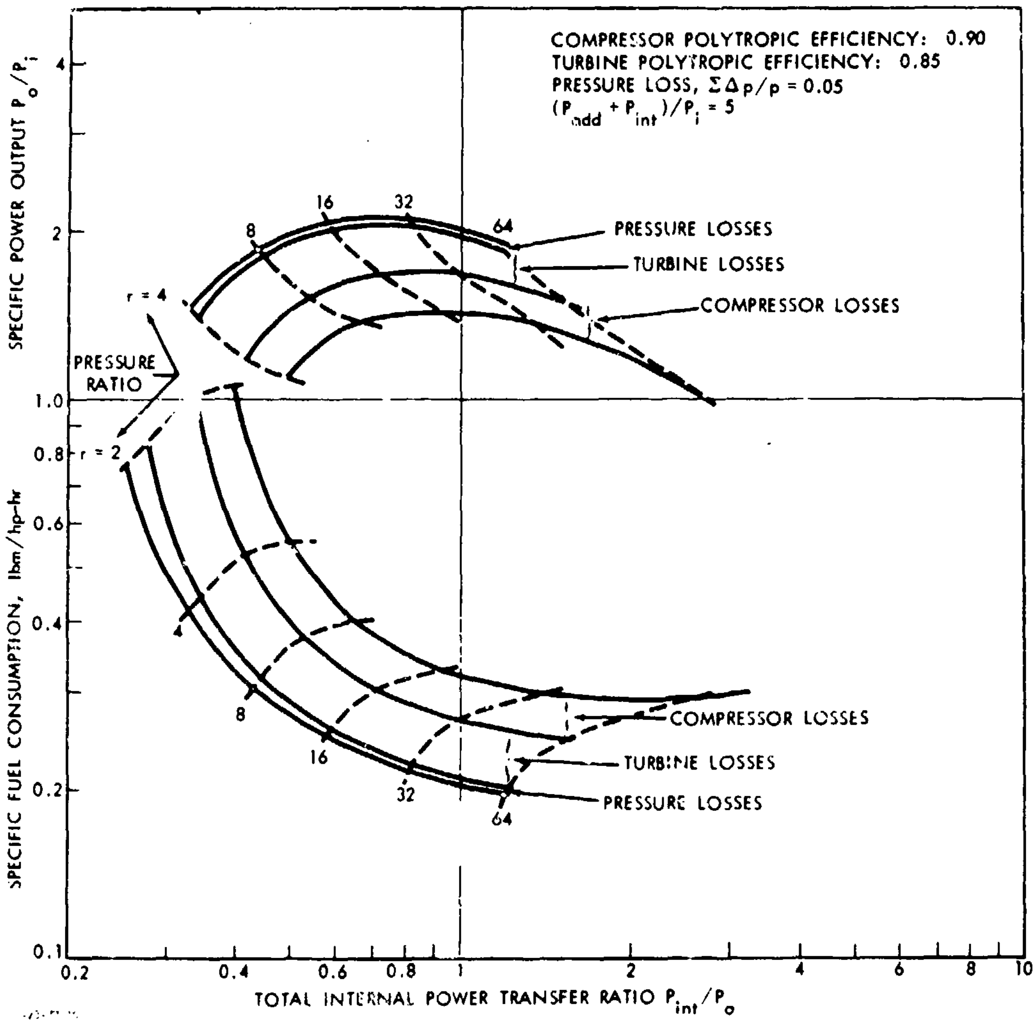

FIGURE IV-14. Impact of component losses on nonregenerated Brayton-cycle (CBE) performance.

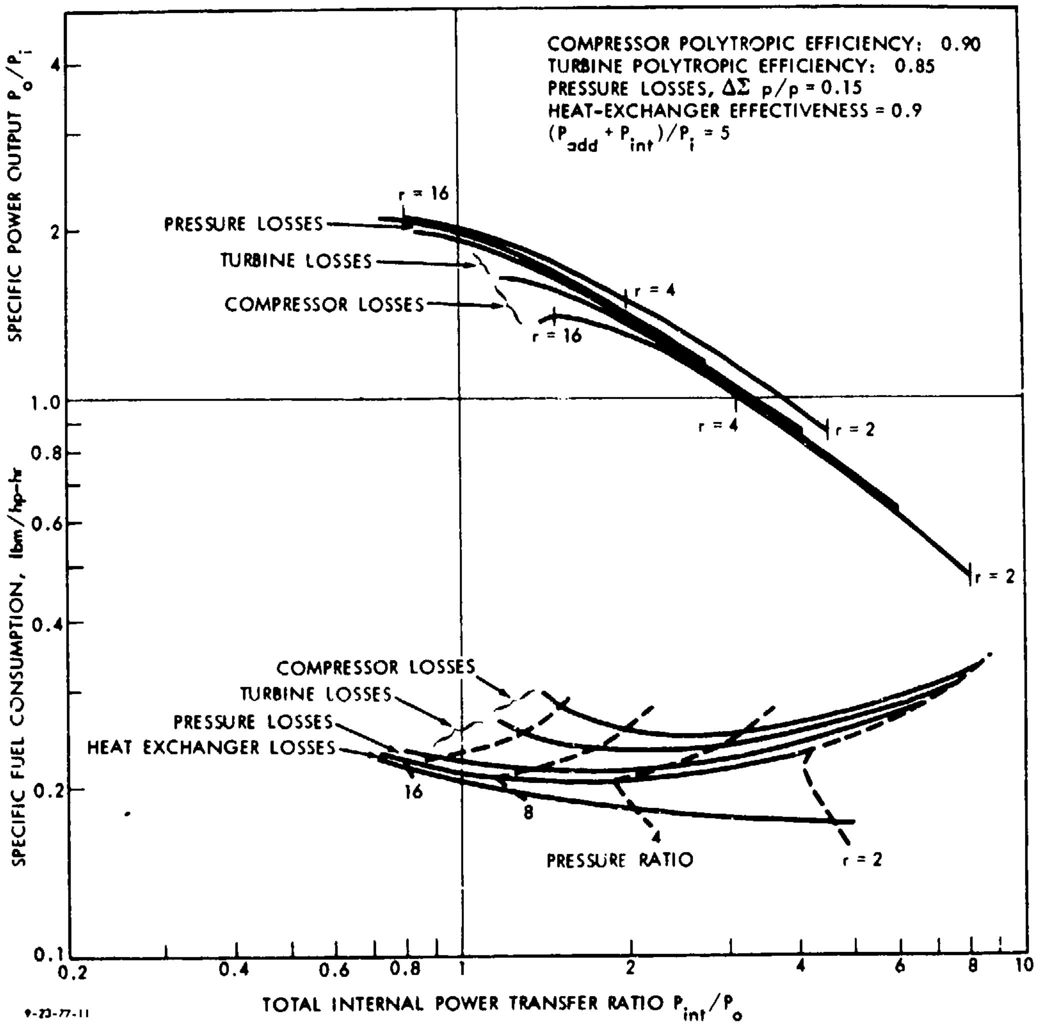

FIGURE IV-15. Impact of component losses on regenerated Brayton-cycle performance.

can be expected. Current simple-cycle engines operating at pressure ratios in the range 16-25 and specific power additions slightly less than 5 achieve values of specific fuel consumption in the vicinity of 0.37 lb/hr-hp, as compared to values of 0.32-0.33 indicated in Fig. IV-14; thus the aggregate impact of the losses is somewhat underestimated. Similar comments apply to the regenerated cycle. Nevertheless, the results are of sufficient accuracy to indicate the importance of the losses in determining actual performance. For example, for the simple-cycle, even these modest losses increase the attainable sfc from a level of about 0.2 to a minimum of 0.3--which represents a loss of 23 percentage points in thermal efficiency. As indicated in Appendix E, this impact of losses can be reduced in one of two ways--either by decreasing the loss values directly, or by increasing the specific power addition (i.e., increasing the maximum temperature). With respect to the individual losses, it can be observed that, in the simple cycle, the turbine loss is dominant, closely followed by the compressor loss; in the regenerated cycle, the heat exchanger loss is substantial, even for the high value of effectiveness assumed. Pressure losses tend to be rather small in either cycle, which accounts for the somewhat better performance of the regenerated cycle compared to the simple cycle.

The previous results refer to the performance at operating conditions which produce the minimum specific fuel consumption, which in gas-turbines is virtually synonomous with maximum-power operation. Of more interest here is the specific fuel consumption at the representative 25% power condition. The detailed estimation of part-power performance of a gas-turbine is a complex proposition, for reasons explored at length in Appendix E. Briefly, however, the sfc of a gas-turbine increases as power is reduced primarily because of the operating characteristics of the compressor, which do not permit a reduction in mass flow rate proportionate to the power decrease, nor

permit maintaining the pressure ratio. As a consequence, pressure ratio decreases as power is reduced, thus reducing the internal power transfer and increasing the ideal sfc, and the maximum cycle temperature is reduced, thus increasing the adverse impact of the losses on specific fuel consumption. In addition, the losses of the individual components tend to be somewhat higher at part power than at full power. The net effect tends to be larger in simple-cycle engines, since all of the internal power transfer is accomplished through the compressor. As an example of the net effect, a typical simple-cycle engine with a full-power pressure ratio of 17 would possess an ideal (full-power) sfc of 0.249 (55% thermal efficiency); current engines of this type achieve an actual sfc of about 0.37 (37% thermal efficiency). At 25% power, the pressure ratio would be perhaps 9, corresponding to an ideal sfc of 0.296 (47% thermal efficiency), and the actual sfc would be about 0.57 (24% thermal efficiency). Thus, the part-power sfc represents a loss of 13 percentage points in thermal efficiency from the full-power value, 8 of which can be attributed to loss of ideal performance, and the other 5 of which can be attributed to the combined effect of reduced maximum temperature and higher component losses.

Based on rather sparse data, it is assumed here that the 25% power sfc, for simple-cycle engines, is 43% greater than the full-power sfc, and for highly regenerated engines, is 20% greater than the full-power value. For the same full-power loss assumptions as in Figs. IV-14 and IV-15, the resulting part-power sfc is shown in Fig. IV-16. It can be observed that, in simple-cycle engines, simultaneous increases in specific power addition (maximum temperature) and internal power transfer (pressure ratio) would improve both the ideal performance and the actual performance. The same is also true for regenerated engines, although it is not so readily apparent from Fig. IV-16. The impact of the losses, however, is substantial; as indicated

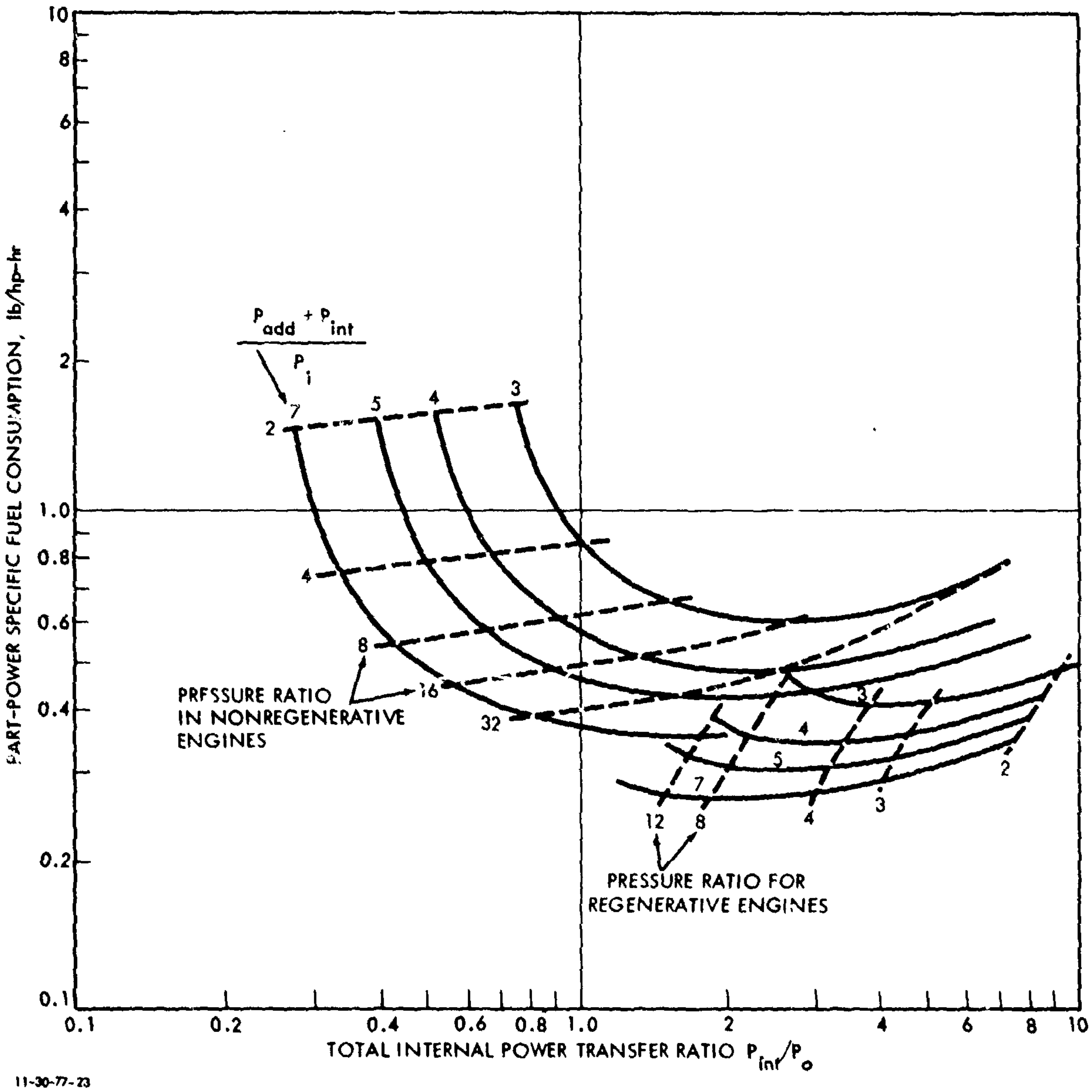

FIGURE IV-16. Part-power performance of Brayton-cycle engines.

earlier, a typical current simple-cycle engine may operate at a full-power ideal sfc of 0.25 (55% thermal efficiency), but with an actual part-power sfc of 0.57 (24% thermal efficiency).

c. **Weight, Size, and Performance Relationships**. As with other types of engines, the sfc_e-sw_e-sv_e relationship of gas-turbine engines can be considered to be influenced by three factors: power level, design choice, and state of technology.

In principle, power scaling in a gas turbine is determined by the necessity to maintain the same tip speeds and relative fluid velocities in rotating components (which, to first order, maintains efficiency and stress levels constant). This results in a linear dimension which increases as the square root of power level and a rotational speed which is inversely proportional to the linear dimension. Hence, assuming the weight is proportional to the cube of the linear dimension, the scaling laws are of the form

$$\frac{W}{P_o} \sim P_o^{1/2}$$

and

$$N \sim P_o^{-1/2} ,$$

where W is the engine weight, P_o is the output power, and N is the characteristic rotational speed. As with other engines, however, there are size levels below which the weight does not scale as the cube of the linear dimension, and below which the loss levels increase. In gas turbines, both of these size levels appear to be in the range of 1000-10,000 hp. In the following discussion, attention will be largely devoted to engines in the nominal range of 10,000-20,000 hp, 5000-7500 rpm, with the understanding that the previous scaling laws apply for larger power levels, and that some adjustment to loss levels are required for lower power levels.

At a given power level, many design choices involving cycle parameters and tradeoffs among loss, weight, and size of the various components of gas-turbine engines are available: at one level, tradeoffs between the cycle parameters (e.g., internal power transfer by either compression and/or heat exchange) and the resulting component characteristics is possible; at another level, tradeoffs between component loss, weight, and size and the resulting impact on cycle performance is possible. For convenience of analysis, as well as for orientation purposes, the examination of such tradeoffs here will begin from a baseline which is representative of the makeup of current state-of-the-art engines.

For simple-cycle gas turbines for surface-vehicle applications, a specific weight of 0.37 lb/hp, a part-power sfc of 0.58, a pressure ratio of 16-20, and a maximum cycle temperature of 2200-2400°F is estimated to be reasonably representative of the current state of the art. A typical component weight breakdown would be as follows:

Component	Percentage of Total Weight	Component Weight / Output Power (lb/hp)	Component Weight / Component Power (lb/hp)
Compressor	19	0.069	.051
Combustor	4	0.016	.006
Turbine	34	0.127	.054
Ducting	26	0.100	--
Other	17	0.063	--

It can be observed that the specific weights of the compression and expansion components are about two orders of magnitude less than those of reciprocating engines. For regenerated cycles, no suitable data was found for existing engines; accordingly, an estimate of the component weight breakdown of such an engine is based upon adding what is estimated to be a state-of-the-art

heat exchanger to a current simple-cycle engine. The resulting engine would have a specific weight of about 1.7 lb/hp, a part-power sfc of 0.43, a pressure ratio of 6, and a heat-exchanger effectiveness of 0.80. The resulting weight breakdown would be:

Component	Percentage of Total Weight	Component Weight / Output Power (lb/hp)	Component Weight / Component Power (lb/hp)
Compressor	3	0.048	.054
Combustor	1	0.016	.007
Turbine	6	0.11	.058
Heat Exchanger	80	1.40	.95
Ducting	6	0.10	--
Other	4	0.063	--

Obviously, such an engine is rather completely dominated by the heat exchanger.

The component loss-weight-size characteristics relevant to gas turbines are examined in some detail in Appendix E (radial turbomachinery, combustors, heat exchangers) and Appendix F (axial turbomachinery). These relationships form the basis of synthesizing the sfc_e-sw_e-sv_e relationships for present and future gas turbines, and are briefly discussed here. It is to be emphasized that these relationships must be viewed as highly tentative, pending comparison and reconciliation with more actual component data than was available in the present investigation.

For specified material properties, the basic relationships for the specific weight of work-transfer components (compressors and turbines) are approximately as follows. For centrifugal compressors,

$$\frac{W_c}{P_c} \sim \left(\frac{\dot{m}}{\rho}\right)^{1/2} \left(\frac{p+K}{\rho}\right) \frac{1}{\psi^{11/4}} \sim \left(\frac{P_c}{\rho}\right)^{1/2} \left(\frac{p+K}{\rho}\right) \frac{1}{\Delta H^{1/2} \psi^{11/4}} \;;$$

for axial compressors,

$$\frac{W_c}{P_c} \sim \left(\frac{\dot{m}}{\rho}\right)^{1/2} \left(\frac{p+K}{\rho}\right) \frac{\rho^{1/3}}{\psi^{2/3}} \sim \left(\frac{P_c}{\rho}\right)^{1/2} \left(\frac{p+K}{\rho}\right) \frac{\rho^{1/3}}{\Delta H^{1/2} \psi^{2/3}} \quad ;$$

and for axial turbines:

$$\frac{W_t}{P_t} \sim \left(\frac{\dot{m}}{\rho}\right)^{1/2} \left(\frac{p+K}{\rho}\right) \frac{\rho^{1/2}}{f(\psi)} \sim \left(\frac{P_t}{\rho}\right)^{1/2} \left(\frac{p+K}{\rho}\right) \frac{\rho^{1/2}}{\Delta H^{1/2} f(\psi)} \quad .$$

In these relationships, p is the maximum gas pressure, ρ is the minimum gas density, $\dot{m}$ is the mass flow rate, ψ is the aerodynamic loading coefficient [stage enthalpy change/(tip speed)^2] which is proportional to component loss level, ΔH is the total enthalpy change, and K is related to the ratio of the weights of rotating parts to stationary parts. All of these relationships have the same general features in that (1) specific weight scales as the square root of power level and mass flow rate, (2) depending upon the relative weights of rotating and stationary parts, specific weight scales between the zero and first power of the pressure ratio, and (3) the relationships are not particularly simple. The influence of material properties is also dealt with in the appropriate Appendices, but these are not amenable to a simplified discussion here.

Of the two heat-transfer components, combustors and heat exchangers, the latter have the most dominant impact on Brayton cycles, and deserve some discussion here. Fundamentally, the relationship between heat exchanger size and weight, effectiveness, and pressure loss is of two different forms, depending upon whether the flow is laminar or turbulent. Only laminar flow is discussed here, since it contains all of the essential features, and is the simpler case. The fundamental relationship between heat transfer and friction dictates that in

laminar flow, the specific weight of a heat-exchanger core does not depend directly upon pressure loss:

$$\frac{W_{HX}}{P_{HX}} \sim \frac{1}{1-\varepsilon}\left(\frac{d_h}{k\Delta T_a}\right)\left(\frac{d_h}{4}\right)\left(\frac{t}{d_h}\right) , \qquad \text{(IV-1)}$$

where W_{HX} is the weight of core, P_{HX} is the heat-transfer rate in the heat exchanger, d_h is the hydraulic diameter of the passages, k is the thermal conductivity, ΔT_a is the maximum temperature difference available (maximum temperature of hot fluid--minimum temperature of cold fluid), t is the wall thickness, and ε is the effectiveness. The origin of the terms is readily evident: $k\Delta T_a/d_h$ is a characteristic heat-transfer rate per unit surface area based on the maximum possible temperature difference; $1-\varepsilon$ is the ratio of the actual temperature difference through which heat is transferred to the maximum available difference; $4/d_h$ is the surface-area-to-volume ratio of the core; and t/d_h is the ratio of metal volume to void volume.

In laminar flow, the pressure loss of a heat exchanger with a given level of effectiveness determines only the resulting geometry, characterized here by an aspect ratio, a_r, defined as the ratio of the flow length to the square root of the face area. The aspect ratio is quite an important parameter for heat exchangers, since low aspect ratios tend to require large weights and volumes of ducting to provide satisfactory entry and exit of the fluid to the heat-exchanger core. As it happens, the relationship between specific weight and aspect ratio is the same for laminar or turbulent flow:

$$\frac{W_{HX}}{P_{HX}} \sim \frac{1}{(1-\varepsilon)^{3/4}(P_{loss}/P_{HX})^{3/4}}\left(\frac{P_{HX}}{\rho}\right)^{1/2}\frac{1}{(c_p\Delta T_a)^{3/4}}\,\frac{1}{\rho}\left(\frac{t}{d_h}\right)a_r , \qquad \text{(IV-2)}$$

where P_{loss} is the power required to overcome the pressure loss, ρ is the fluid density, and c_p is the specific heat. It can be observed that, at constant aspect ratio, the specific weight is proportional to $P_{HX}^{1/2}$ and is independent of k or d_h. On the other hand, with no constraint on aspect ratio, the specific weight (for laminar flow, Eq. IV-1) is proportional to d_h^2/k and is independent of power level. The implication is that as power level is increased, or as component design variables (e.g., the hydraulic diameter) are changed to reduce the specific weight, the aspect ratio becomes smaller; clearly, at some point, the ducting weight will become the dominant component. Thus, compact heat exchangers tend to become aspect-ratio limited and follow the scaling law in Eq. IV-2; as a practical matter, this means that high-power-level heat exchangers will have larger hydraulic diameters than those of low power level.

The preceding relationships governing component behavior, in combination with baseline data points, can be used to construct an sfc_e-sw_e relationship applicable to the current state of the art in engine technology.* The relationship which

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*Inasmuch as the relationship used for specific weight is not explicitly stated in Appendix E, it is recorded here:

$$\frac{W}{P_o} = \left[\left(\frac{W_c}{P_c}\right)_r\left(\frac{P_c}{P_o}\right) + \left(\frac{W_T}{P_T}\right)_r\left(\frac{P_c}{P_o}\right) + \left(\frac{W_B}{P_B}\right)_r\left(\frac{P_{add}}{P_o}\right) + \left(\frac{W_D}{P_o}\right)_r\right]\frac{(P_o/P_i)_r^{1/2}}{(P_o/P_i)^{1/2}}$$

$$+ \left(\frac{W_{HX}}{P_{HX}}\right)_r \frac{[(1-\varepsilon)_r\Delta T_r]}{[(1-\varepsilon)\Delta T]} + \frac{W_o}{P_o} \quad ,$$

where $(W_c/P_c)_r$ is the reference value of the specific weight of the compressor (taken as 0.051 lb/hp), $(W_T/P_T)_r$ is the reference value of the specific weight of the turbine (taken as 0.054 lb/hp), $(W_B/P_B)_r$ is the reference value of the specific weight of the combustor (taken as 0.006 lb/hp), $(W_D/P_o)_r$ is the reference value of the ducting specific weight (taken as 0.10 lb/output horsepower), $(P_o/P_i)_r$ is the reference value of (continued on next page)

results is shown in Fig. IV-17, with data from some existing engines. (Potential limits for gas-turbine engines, as discussed subsequently, are also shown in Fig. IV-17.) The low-specific-weight portion of the curve applies to simple-cycle engines, the high-specific-weight portion of the curve applies to regenerated-cycle engines. The relationship is intended to be applicable to engines in the nominal range of 10,000-20,000 horsepower; only one data point (at a specific weight of 0.37 lb/hp--the baseline point) is for an engine of this power level. The other engines are generally in the vicinity of 1000 hp; it is estimated that in this size range, the sfc would be about 20% greater than that indicated in Fig. IV-17, due to the increased losses associated with smaller sizes. This appears to be generally consistent with the data. Obviously, uncertainties associated with heat exchanger size, and its effect on part-power performance, have a large influence on the nature of the high-specific-weight portion of the curve.

d. Potential Limits for Gas-Turbine Engines. Based upon the previous development, the major impediments to further improvement appear to be the following:

1. Limited internal power transfer, due to the combination of restricted temperature levels (or restricted heat addition) and current component loss levels; in simple-cycle engines, the increase of component loss with increasing pressure ratio is also a limitation. These

*(continued from previous page)
specific power for the previous reference values (1.0), (W_{HX}/P_{HX}) is the reference value of the specific weight of the regenerator (taken as 1.57 lb/hp), ϵ_r, ΔT_r are the reference values of effectiveness and temperature difference available for the heat exchanger (0.9 and 1000°F, respectively), and W_o/P_o is the specific weight of miscellaneous components (taken as 0.063 lb/hp). The heat exchanger specific weight is a factor of 4 greater than that which is estimated to be theoretically possible for the core alone, assuming steel as the material and a hydraulic diameter of 0.05 inch.

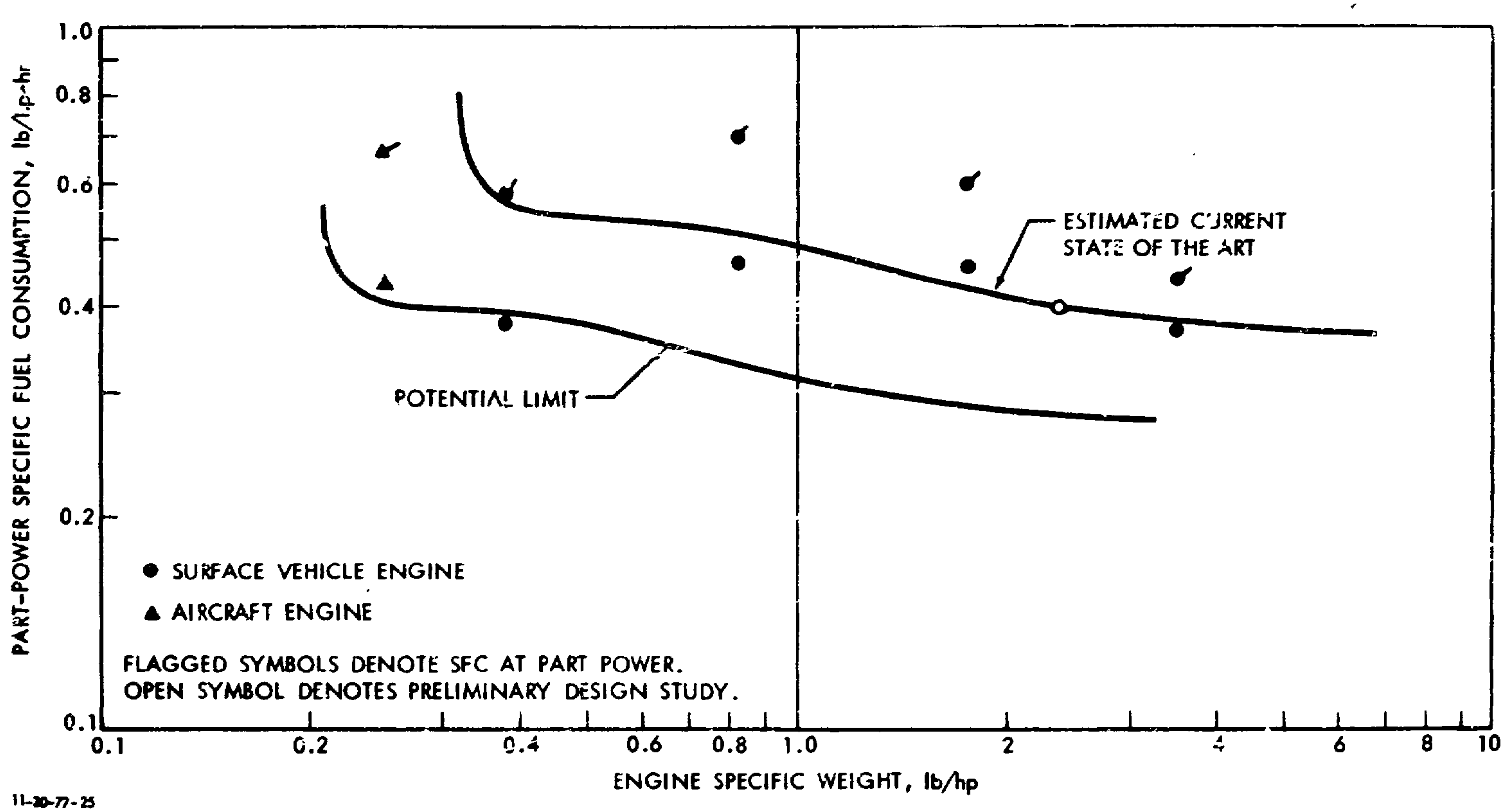

FIGURE IV-17. Specific fuel consumption--specific weight relationships for open Brayton-cycle (gas-turbine) engines.

limitations can be alleviated somewhat by improved high-temperature materials.

2. [illegible] basic level of component losses which, at current temperature levels, increases the specific fuel consumption from an ideal value of about 0.21 (66% thermal efficiency) to a best value of about 0.37 (37% thermal efficiency. There seems to be little prospect for further reductions in component loss levels, except perhaps at lower power levels (~1000 hp).

3. The part-power characteristics of the turbomachinery elements, which require lowering both the internal power transfer and the maximum temperature level at part-power conditions. This effect is stronger in simple-cycles than in regenerated cycles. No fundamental improvements are foreseen.

4. The size and weight of heat exchangers in regenerated-cycle engines. The weight could be alleviated by lightweight (and high-temperature) materials; the size seems to be fundamentally limited by aspect ratio considerations.

Apparently, then, the major prospects for improvement are in higher temperature capability and lighter heat exchangers. It is assumed here that a reasonable limit consists of a maximum temperature level of 3700°F [corresponding to $(P_{add} + P_{int})/P_1 = 7$], which corresponds roughly to stoichiometric operation at modest pressure ratios, while maintaining component loss levels and specific weights at their current levels. Use of the previously developed scaling laws then permits an estimate of the sfc_e-sw_e characteristics to be made, with the results shown in the left-hand portion of Fig. IV-17. The engine specific volume is estimated to be that obtained from densities ranging from 25 lb/ft^3 at lower specific weights (simple-cycle engines) to about 60 lb/ft^3 at the higher specific weights (regenerated-cycle engines). Yet again, it must be emphasized that the

interpretation of these relationships is that the performance of gas-turbine engines cannot reasonably be expected to exceed this limit in the foreseeable future. Attaining such a limit requires essentially uncooled, stoichiometric operation, at low component loss levels and specific weights; known solutions to these difficulties do not currently exist. As before, it is assumed that the relationships shown in Fig. IV-17 apply to engines in the 10,000-20,000 hp range; it seems conceivable that component loss levels at lower power levels could achieve sfc values 10% greater than those for larger engines.

Although the origin of the potential improvements shown in Fig. IV-17 is clear--increase in maximum temperature levels--it is instructive to examine the individual impacts on ideal cycle performance, effects of losses, and relative component size. Taking a typical point on the state-of-the-art curve as a specific weight of 2.3, and a typical point on the potential curve as a specific weight of 1.1, some representative parameters are as follows:

	Current	Limit
Specific Weight, lb/hp	2.3	1.1
sfc, part-power, lb/hp-hr (η)	0.40 (34)	0.31 (44)
sfc, full-power, lb/hp-hr (η)	0.33 (42)	0.26 (54)
Specific power, P_o/P_i	0.87	2.04
Pressure ratio	6	8
Maximum Temperature, ^oF	2140	3700
Heat Exchange Effectiveness	0.85	0.85
Ideal sfc (η)	0.21 (67)	0.18 (77)
Ideal specific power	1.3	2.8
Ideal internal power ratio, P_{int}/P_o	1.6	1.2
Ideal specific internal power, P_{int}/P_i	2	3.5
Ideal specific-heat addition, P_{add}/P_i	2	3.5
Ideal combustor inlet temperature, ^oF	1100	1830

In terms of ideal performance, the sfc improvement is equivalent to 10 percentage points in thermal efficiency, arising from an increase in internal power transfer made possible by the higher temperature; the specific power slightly more than doubles, primarily due to the increase in specific heat addition. The component loss levels are of course the same in both cases; their impact on actual sfc is also essentially the same (25 percentage points in efficiency versus 23). The reason for the constant impact is perhaps not obvious: the impact of a component loss on thermal efficiency can be roughly approximated by

$$\Delta\eta \sim (1 - \eta_c) \frac{P_c}{P_{add}} ,$$

where η_c is an appropriate component efficiency and P_c is the power transferred by the component; in the present case, the power levels of all components scale roughly as P_{add}, and hence the impact remains the same. The actual specific power increases by a greater percentage than the ideal specific power, in accordance with the different percentage change in ideal and actual efficiency values. The essential point is that the decrease in actual sfc is due entirely to the decrease in the ideal sfc. The weights of the components change by approximately the same amount as the specific power, with the heat exchanger remaining the dominant component.

e. Suitable Goals and High-Payoff Technology Areas for Gas-Turbine Engines. As developed in Section III, suitable goals for gas-turbine engines in ground-combat vehicles are in the vicinity of a part-power sfc* of 0.43 lb/hp-hr and a specific weight of 0.6 lb/hp, although goals of a part-power sfc of 0.47 and a specific weight of 0.4 lb/hp would be equally satisfactory.

*The sfc goals are referred to large engines; for the actual engine, they are 10% higher.

For high-speed ship applications, appropriate goals are in the vicinity of a part-power sfc of 0.35 lb/hp-hr and a specific weight of 1.5 lb/hp.

Considering first high-speed ship applications, it can be observed from the current and potential-limit design points discussed above that these goals represent an improvement of slightly more than 1/2 of that which is estimated to be perhaps possible. This translates into the following goals for ideal performance, component loss levels, and component specific weights:

1. An ideal cycle performance of an sfc of 0.193 lb/hp-hr, a specific power output (P_o/P_i) of 1.5, and a maximum temperature of about 2700°F [$(P_{add} + P_{int})/P_i = 5.1$].
2. Maintenance of component loss levels at current best levels.
3. Maintenance of component specific weights at current levels; of particular importance is the heat exchanger, which requires a specific weight of about 0.9 lb per horsepower transferred at these conditions (an effectiveness of 0.85 and an available temperature difference of about 1400°F).

The high-payoff areas are, in order of decreasing estimated impact:

1. High-temperature materials for combustors, turbines, and heat exchangers, to enable the required ideal cycle performance to be obtained.
2. Lightweight materials for heat exchangers, or other concepts to reduce the size and weight required; any reduction in the size and weight of heat exchangers necessary to achieve a given performance will enable a reduction in the necessary maximum temperatures (for example, a 1/3 reduction in the weight of heat exchangers would enable the performance goals to be achieved at a maximum temperature of 2400°F).

3. Concepts to improve the part-power performance--a minimum of about 10 percentage points in thermal efficiency is lost here.

With respect to ground combat-vehicle applications, it has been previously pointed out in Section III that a modestly regenerated engine is the appropriate choice. Reasoning similar to that applied to the high-speed ship application produces a similar set of goals:

1. An ideal cycle performance of an sfc of 0.217 lb/hp-hr, a specific power output (P_o/P_i) of 1.9, and a maximum temperature of about 2500°F [$(P_{add} + P_{int})/P_i = 4.7$].
2. Maintenance of component loss levels at current best levels.
3. Maintenance of component specific weights at current levels; the heat exchanger remains of considerable importance (although not as important as in a highly regenerated engine), and requires a specific weight of about 0.70 lb per horsepower transferred at these conditions (an effectiveness of about 0.65 and an available temperature difference of about 600°F).

The higher payoff areas are the same as for high-speed ship applications, with the exception that the payoff for lightweight heat exchangers is somewhat less.

5. Closed Brayton-Cycle Engines

a. Ideal Performance. The ideal closed Brayton cycle is fundamentally identical to the regenerated open Brayton cycle; the differences are that additional heat exchangers are required to add heat to and reject heat from the working fluid. The basic cycle parameters are the pressure ratio, the ratio of maximum cycle temperature to the minimum cycle temperature, and the properties of the working fluid. The total internal power transfer, as defined here, consists of that required for compression, that transferred through the regenerator, and that transferred through the heater and cooler.

The ideal performance of the closed Brayton cycle is developed in Appendix F and is shown in Fig. IV-18, for a monatomic gas (the ideal performance depends only upon the ratio of specific heats). Again, the parameter $(P_{add} + P_{int})/P_i$ is indicative of the maximum cycle temperature (a value of 3 corresponds to a maximum temperature 1620°F for a minimum cycle temperature of 60°F).

Although there are no closed Brayton-cycle engines in existence for surface-vehicle applications, some rather complete design studies indicate that a state-of-the-art engine would operate in the vicinity of $(P_{add} + P_{int})/P_i = 3$ (1620°F) and $P_{int}/P_o \approx 5$ (a pressure ratio of about 2). Further improvements in ideal performance are obviously governed by the same factors as open Brayton-cycle engines: increases in maximum cycle temperatures which increase the specific power output and which permit greater levels of internal power transfer to be obtained, thus reducing the specific fuel consumption.

b. Actual Performance. As with gas-turbine engines, the losses in closed Brayton-cycle engines are easily identifiable with the power transfer processes and corresponding components. Compressor, turbine, regenerator, and ducting losses are characterized as for gas turbines; the major additional sources of loss are the heater, which is characterized by an efficiency defined as the ratio of the heat added to the working fluid to the fuel energy used, and the cooler, which can be characterized by an effectiveness and a pressure loss. The impact of cooler effectiveness is to raise the minimum cycle temperature for a given heat-rejection-medium temperature and, as such, is not charged directly to the cycle here. The effect on cycle performance, in terms of energy transfer parameters, is to reduce the value of $(P_{add} + P_{int})/P_i$ for a given maximum temperature. It is to be noted that since the cycle is closed, there is no necessity to sustain real gas losses.

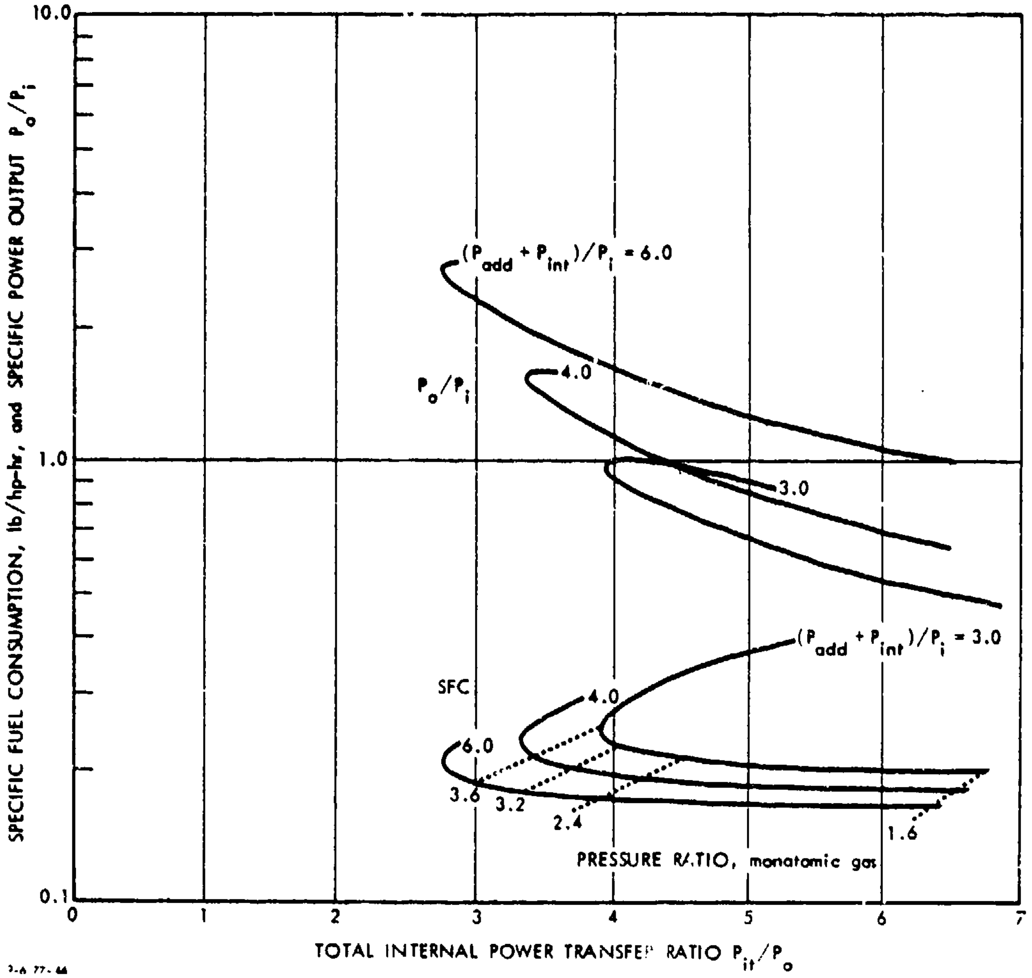

FIGURE IV-18. Performance characteristics of ideal closed-Brayton cycles.

The impact of these individual losses on ideal performance is estimated in Appendix E. Representative results are shown in Fig. IV-19, for assumed compressor and turbine efficiencies of 90%, a regenerator effectiveness of 0.9, and a heater efficiency of 0.9, all of which are believed to be representative of a reasonable design. More detailed design studies indicate a specific fuel consumption at these conditions of about 0.34 lb/hp-hr, which compares well with the minimum value of 0.32 shown in Fig. IV-19.* The collective impact of these rather modest loss levels on engine performance is substantial; they increase the sfc from an ideal level of about 0.2 to a minimum of about 0.32, corresponding to a reduction in thermal efficiency from 69% to 43%. With respect to individual losses, it can be observed that the regenerator effectiveness has the most significant influence on sfc, with the other losses being of approximately equal importance.

The preceding performance is representative of full-power operation. However, since the cycle is closed, it is possible (but not easy) to control the power level by changes in mass flow rate through the mechanism of changing the pressure level in the system. Thus, the components and the cycle tend to operate at the same efficiencies at all power levels, and hence it is believed that full-power performance is also representative of part-power performance.

It can be inferred from Fig. IV-19 (and is demonstrated in Appendix F) that increases in maximum temperature, and resultant increases in internal power transfer, will improve both the ideal and the actual performance; the impact of the losses, however, remains substantial.

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*It is noted that in the ordinate of Fig. IV-19, the indicated pressure ratio applies to both ideal and actual cycles, but that the internal power transfer ratio applies only to the actual cycle.

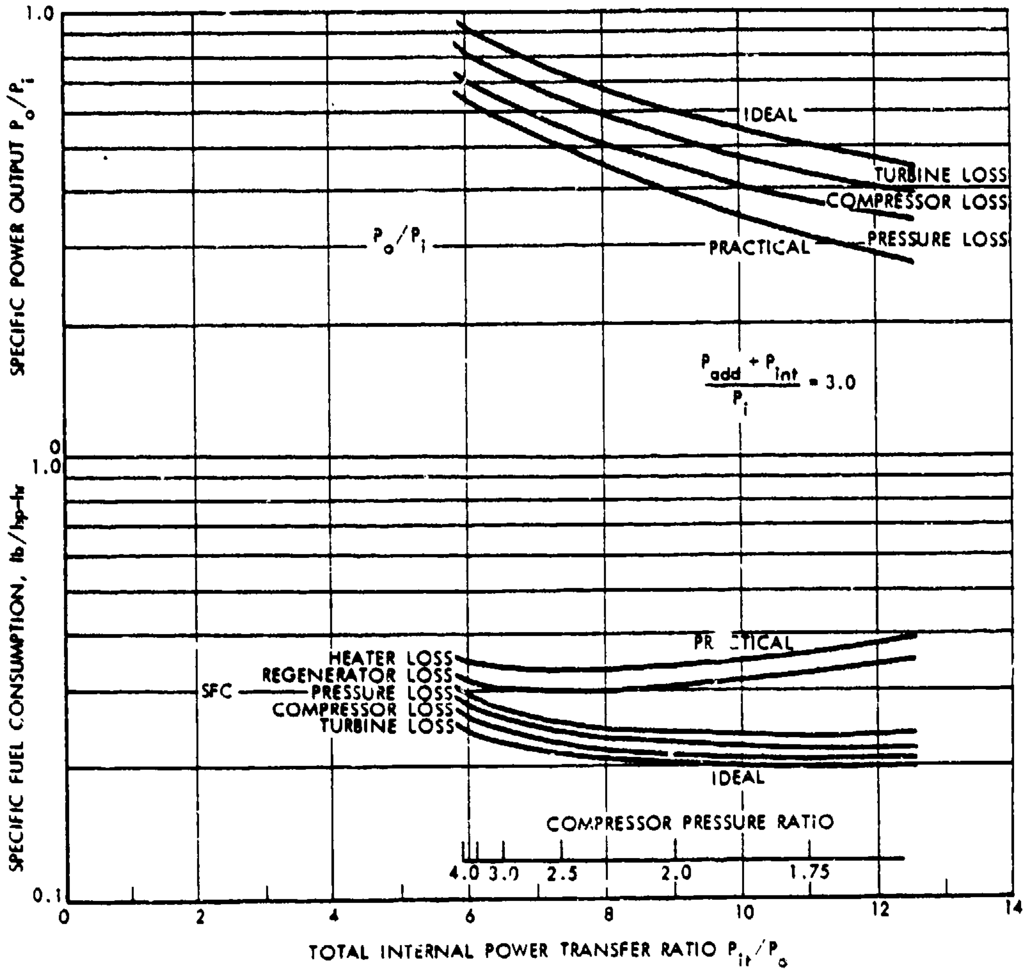

FIGURE IV-19. Influence of component losses on closed Brayton-cycle engine performance.

c. <u>Weight, Size, and Performance Relationships</u>. Power-scaling for closed Brayton-cycle engines is identical to that for gas turbines: namely, above some power level, the specific weight and volume scale directly, and the speed inversely, with the square root of power level. The possibility of selecting the nominal pressure level in a closed-cycle engine introduces an additional free variable; in general, the specific weight scales as (pressure level)$^{-1/2}$, and the specific volume scales as (pressure level)$^{-3/2}$. As the pressure level is increased, however, the size of an engine decreases to a point where these scaling laws do not apply. In the discussion here, attention is largely devoted to engines in the nominal range of 10,000-20,000 horsepower, 10,000-15,000 rpm, and a pressure level of about 300 psia, with the understanding that the previous scaling laws apply to higher power levels and lower pressure levels.

At a given power level, the closed Brayton-cycle engine offers perhaps more design choices than any other engine: as examples, tradeoffs between heater size and efficiency, power transfer by compression and regeneration, regenerator size and effectiveness, regenerator size and pressure loss, and turbomachinery component size and efficiency are all possible. Each individual tradeoff produces a relationship between engine specific weight (or volume) and sfc. The primary interest here is the envelope of such individual curves and, as a consequence, the major tradeoff examined is that of regenerator weight (and size). If the other design choices are reasonable, this tradeoff will produce an sfc_e-sw_e relationship which is hopefully a reasonable approximation to the actual envelope. Accordingly, an existing design study will be used as a basis for the other design choices.

The current state of the art of closed Brayton-cycle engines for vehicular applications, as defined by design studies, can be represented by a specific weight of 14 lb/hp, an sfc of 0.34 lb/hp-hr, a maximum heater-gas temperature of 2900°F, and

a maximum cycle temperature of about 1600°F, with helium as the working fluid. A typical component weight breakdown would be as follows:

Component	Percentage of Total Weight	Component Weight / Output Power (lb/hp)	Component Weight / Component Power (lb/hp)
Turbomachinery	4	0.6	0.22
Regenerator	32	5.1	1.1
Cooler	9	1.4	1.31
Heater	45	7.0	3.30
Ducting	10	1.5	--

Obviously, the weight and size of closed Brayton-cycle engines is dominated by the heater and the regenerator, in that order.

The component loss-weight-size characteristics relevant to closed Brayton-cycle engines are identical to those for gas turbines, previously discussed, and are developed in Appendices E and F. These relationships can be used to construct an sfc_e-sw_e relationship applicable to the estimated current state of the art in engine technology.* The relationship which results

*The relationship used for weight determination, not explicitly stated in Appendix F, is as follows:

$$\frac{W}{P_o} = \left(\frac{W_{TM}}{P_{TM}}\right)_r \left(\frac{P_{TM}}{P_o}\right) + \left(\frac{W_R}{P_R}\right)_r \frac{[(1-\varepsilon_r)\Delta T_r]}{[(1-\varepsilon)\Delta T]} \left(\frac{P_R}{P_o}\right)$$

$$+ \left(\frac{W_H}{P_H}\right)_r \left(\frac{P_H}{P_o}\right) + \left(\frac{W_c}{P_c}\right)_r \left(\frac{P_c}{P_o}\right) .$$

where $(W_{TM}/P_{TM})_r$ is the value of the specific weight of the turbomachinery (taken as 0.22 lb/hp transferred), $(W_R/P_R)_r$ is the reference value of the specific weight of the regenerator (taken as 0.77 lb/hp transferred at conditions ε_r = 0.95, ΔT_r = 1000), $(W_H/P_H)_r$ is the value of the specific weight of the heater (taken as 3.30 lb/hp transferred), and $(W_c/P_c)_r$ is the specific weight of the cooler (taken as 1.30 lb/hp transferred). The other quantities are power transfer/power output ratios, which are cycle parameters.

is shown in Fig. IV-20, with the results of one state-of-the-art design study. (Potential limits for closed Brayton-cycle engines, as discussed subsequently, are also shown in Fig. IV-20.) The low-specific-weight portion of the curve is related to lower regenerator effectiveness, the high-specific-weight portion to higher regenerator effectiveness. Clearly, any uncertainties in regenerator size and performance will reflect in corresponding uncertainties in this relationship.

d. Potential Limits for Closed Brayton-Cycle Engines. Based on the previous development, the major impediments to further improvements in closed Brayton-cycle engines appear to be the following:

1. Limited internal power transfer, due to the restricted temperature levels (or heat addition). This can be alleviated somewhat by improved high-temperature materials.
2. The basic level of component losses which, at current temperature levels, increases specific fuel consumption from an ideal value of about 0.22 (64% thermal efficiency) to a value of about 0.35 (39% thermal efficiency). There seems to be little prospect for further reductions in basic component loss levels.
3. The weight and size associated with the various heat exchangers, particularly the heater and the regenerator (which account for about 3/4 of the engine weight). Reduction of the weight could be achieved by use of lightweight (and high-temperature) materials, and by use of passage sizes smaller than those usually considered. The latter would also reduce the size.

As a reasonable limit to improvements, it is assumed here that it might be possible to attain (1) a maximum heater-gas temperature of 4000°F (stoichiometric operation in air); (2) a maximum cycle temperature of 2660°F [corresponding to

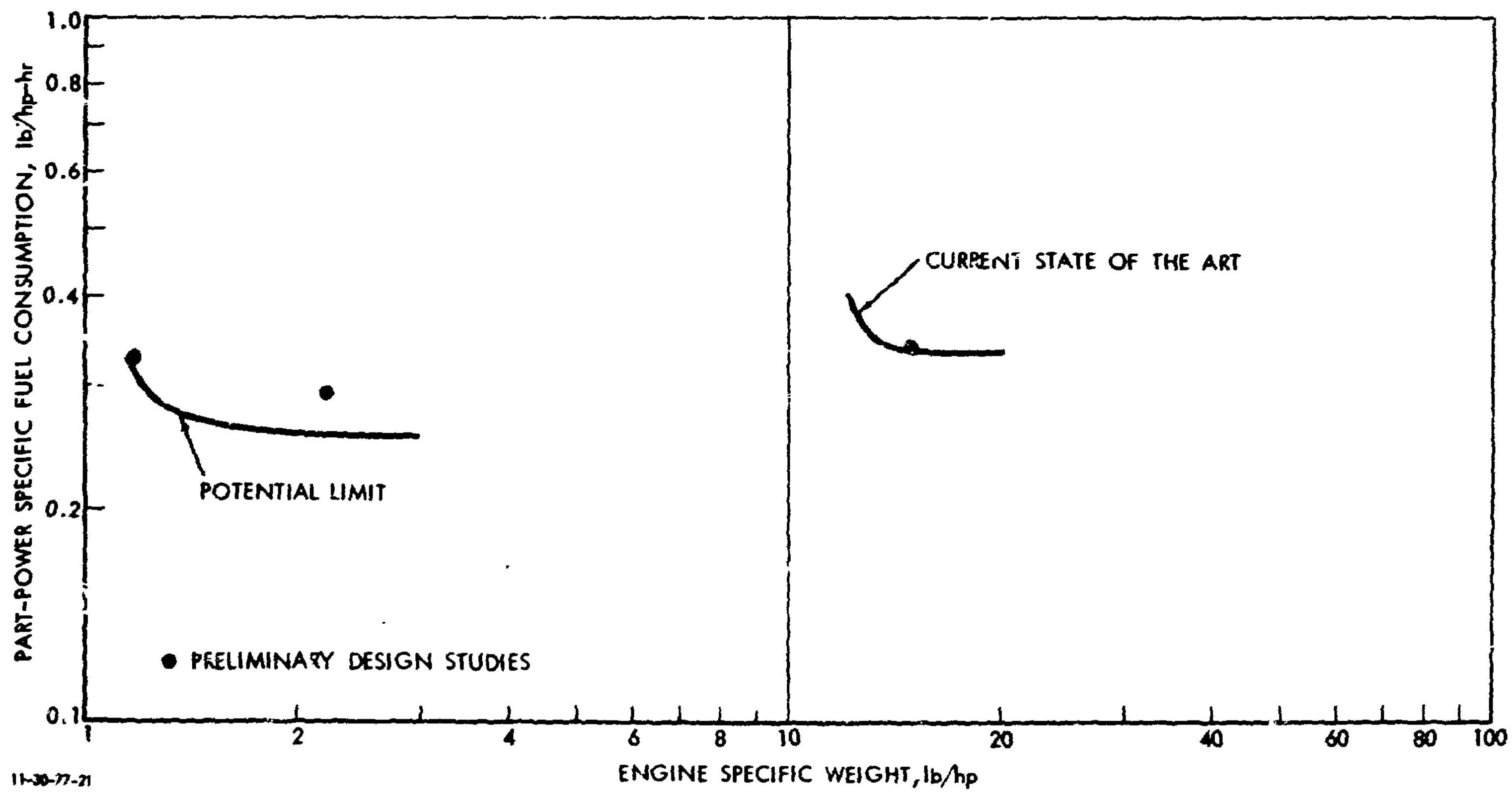

FIGURE IV-20. Specific fuel consumption--specific weight relationships for closed Brayton-cycle engines.

$(P_{add} + P_{int})/P_i = 6$], and (3) reductions in heat exchanger passage sizes to about 0.10 in., while maintaining other component loss levels and specific weights at their current levels. The previously developed component relationships* then permit an estimate of the sfc_e-sw_e characteristics to be made, with the results shown in the left-hand portion of Fig. IV-20. The engine specific volume is estimated to be that obtained from a density of about 70 lb/ft^3. Also indicated in Fig. IV-20 are results for two recent advanced design studies. Once again, it is emphasized that the interpretation to be placed on these relationships is that the performance of closed Brayton-cycle engines cannot reasonably be expected to exceed these limits in the foreseeable future; technical solutions which permit these limits are not at present known.

It is useful to examine the individual improvements in ideal cycle performance, impact of losses and relative component size implied by the relationships in Fig. IV-20. Taking a typical point on the state-of-the-art curve as a specific weight of 12.9 lb/hp, and a typical point on the potential curve as a specific weight of 1.6 lb/hp, some representative parameters are as follows:

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*The weight relationship is identical in form to that used previously, except that the following values were used: $(W_R/P_R)_r = 0.35$, $(W_H/P_H)_r = 0.2$[illegible] $(T_{HE}/1700)$ where T_{HE} is the helium temperature entering the heater; and $W_c/P_c = 0.22$. All of these values correspond to four times that which is estimated to be theoretically possible for the weight of the core alone, with 0.10 in. hydraulic diameter.

$(P_{add} + P_{int})/P_1 = 6]$, and (3) reductions in heat exchanger passage sizes to about 0.10 in., while maintaining other component loss levels and specific weights at their current levels. The previously developed component relationships* then permit an estimate of the sfc_e-sw_e characteristics to be made, with the results shown in the left-hand portion of Fig. IV-20. The engine specific volume is estimated to be that obtained from a density of about 70 lb/ft^3. Also indicated in Fig. IV-20 are results for two recent advanced design studies. Once again, it is emphasized that the interpretation to be placed on these relationships is that the performance of closed Brayton-cycle engines cannot reasonably be expected to exceed these limits in the foreseeable future; technical solutions which permit these limits are not at present known.

It is useful to examine the individual improvements in ideal cycle performance, impact of losses and relative component size implied by the relationships in Fig. IV-20. Taking a typical point on the state-of-the-art curve as a specific weight of 12.9 lb/hp, and a typical point on the potential curve as a specific weight of 1.6 lb/hp, some representative parameters are as follows:

*The weight relationship is identical in form to that used previously, except that the following values were used: $(W_R/P_R)_r = 0.35$, $(W_H/P_H)_r = 0.20\ (T_{HE}/1700)$ where T_{HE} is the helium temperature entering the heater; and $W_c/P_c = 0.22$. All of these values correspond to four times that which is estimated to be theoretically possible for the weight of the core alone, with 0.10 in. hydraulic diameter.

	Current	Limit
Specific weight, lb/hp	12.9	1.6
sfc, lb/hp-hr (η)	0.35 (39)	0.26 (53)
Specific power, P_o/P_i	0.45	1.1
Maximum heater-gas temperature, ^oF	2900	4000
Maximum helium temperature, ^oF	1620	2660
Pressure ratio	2.5	3.0
Regenerator effectiveness	0.95	0.95
Ideal sfc (η)	0.22 (64)	0.19 (74)
Ideal specific power, P_o/P_i	0.75	1.5
Ideal helium heater inlet temperature, ^oF	980	1550
Turbomachinery weight/output power	0.72	0.43
Regenerator weight/output power	2.9	0.57
Cooler weight/output power	1.7	0.15
Heater weight/output power	7.6	0.46

In terms of ideal performance, the sfc improvement is equivalent to 10 percentage points in thermal efficiency, arising from an increase in internal power transfer made possible by the higher cycle temperature; the specific power doubles, primarily due to the increase in heat addition. The impact of the component loss levels is reduced slightly (25 percentage points to 21 percentage points), probably due to a slightly less than optimum choice b tween pressure ratio and regenerator heat transfer. The weights of the components change due to changes in their power levels relative to the power output (typically, by somewhat less than a factor of 2), due to changes in their basic weight-loss relationship (a factor of about 2 for the regenerator, a factor of 10 for the heater, a factor of 6 for the cooler) brought about by (the assumed) smaller passage sizes.

e. Suitable Goals and High-Payoff Technology Areas for Closed Brayton-Cycle Engines. As developed in Section III, suitable goals for closed Brayton-cycle engines in high-speed

ship applications are in the vicinity of an sfc of 0.29 lb/hp-hr and a specific weight of 5 lb/hp. It can be observed from the representative current and potential-limit design points discussed above that these goals represent an improvement of about 70% of that which is estimated to be perhaps possible. If it is presumed that the individual elements (ideal cycle performance, loss impact, component weight and size) of the potential limit performance are equally difficult to obtain, then one suitable set of goals would be that obtained by interpolation, as follows:

1. An ideal cycle performance of an sfc of 0.195 lb/hp-hr (71% thermal efficiency), a specific power output (P_o/P_i) of 1.2, and a maximum cycle temperature of 2200°F [$(P_{add}/P_{int})/P_i \approx 4.1$].
2. Maintenance of component loss levels at current best levels.
3. Reduction of heat exchanger size and weight: for the regenerator, a specific weight of 0.45 lb/hp transferred, at nominal conditions of an effectiveness of 0.95 and an available temperature difference of 1000°F; for the cooler, a specific weight of 0.50 lb/hp transferred; for the heater, a specific weight of 1.2 lb/hp transferred. Also required is a maximum heater-gas temperature of 3600°F.

The high-payoff areas are, in order of decreasing estimated impact:

1. High-temperature materials for the heater and the turbine, to enable the required ideal cycle performance to be obtained.
2. Small-passage heat exchangers, particularly for the heater and the regenerator, to enable size and weight reduction. Lightweight materials, or any other concept for transferring heat with reduced size and weight, would also have a high payoff.

6. Stirling Engines

Stirling engines are not treated in the same depth as the other engine types examined here, due primarily to the lack of any detailed data, and the inherent difficulty of isolating processes in this type of engine. Hence, no basis was developed for quantitatively estimating the sfc_e-sw_e relationships, present or future, for Stirling engines. However, the ideal and actual performance of Stirling engines, as developed in Appendix G, provides some useful information.

a. Ideal Performance. The ideal Stirling cycle consists of isothermal compression, regeneration at constant volume, isothermal heat addition and expansion, and regeneration at constant volume. It is a closed cycle, and hence requires both a heater and a cooler. The basic cycle parameters are the compression ratio and the ratio of maximum to minimum temperatures. In terms of the power transfers, the total internal power transfer consists of that required for compression, the heat transfer rate due to regeneration, and the heat transfer rates in the heater and cooler.

The ideal performance of the Stirling cycle is shown in Fig. IV-21, for a gas with a ratio of specific heats of 1.4 (representative of hydrogen, which is the preferred working fluid due to the influence of specific heat on power output per unit mass flow). It can be observed that at modest compression ratios, the ratio of the total internal power transfer to power output is in the range of 3-5.

b. Actual Performance. The major sources of loss in an actual Stirling engine can be categorized as follows:

1. Imperfect regeneration, characterized here by an effectiveness, ϵ_r.
2. Heater losses, characterized here by a heater efficiency, η_h, defined as the ratio of the heat transfer rate to the working fluid to the energy consumption rate of the fuel.

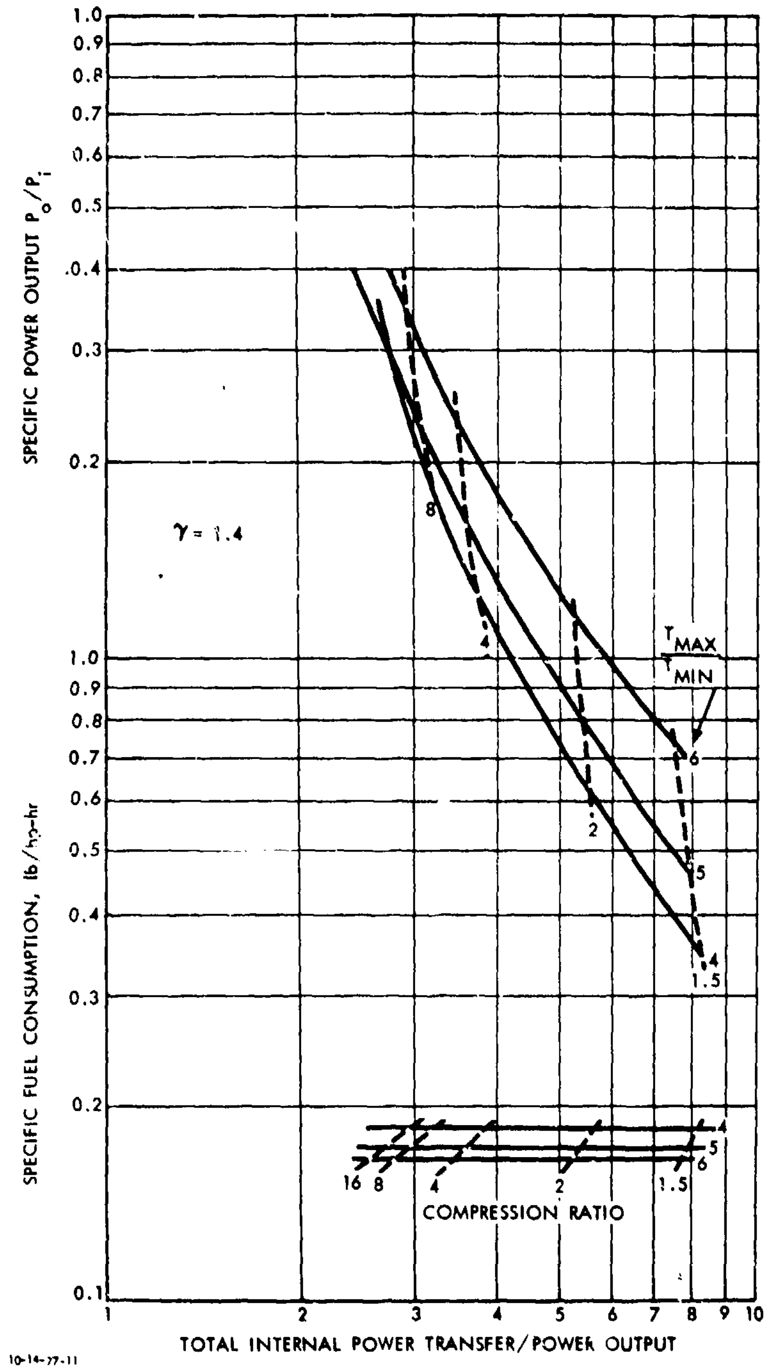

FIGURE IV-21. Performance characteristics of the ideal Stirling engine.

3. Cooler losses, characterized here by $\Delta T_c/T_{min}$, where ΔT_c is the difference between the minimum cycle temperature and the coolant temperature, T_{min}.
4. Losses due to non-isothermal compression and expansion; for purposes of estimating losses, it is assumed here that these processes are isentropic.
5. Frictional losses due to both mechanical and aerodynamic effects, characterized here by an efficiency, η_F, defined as the ratio of the actual power output to that which would be obtained in the absence of frictional effects.

Quantifying such losses in a Stirling engine is a complex matter, and only judgmental estimates are offered for the purposes of representing the actual performance of Stirling engines shown in Fig. IV-22. It can be observed, however, that the minimum sfc is estimated to be about 0.37, which is reasonably consistent with best-sfc values obtained in actual engines, and the minimum occurs in the compression ratio of 3 to 4, which seems to be the range in which Stirling engines currently operate.

The losses clearly have a large impact, roughly doubling the sfc from the ideal (Carnot) value. The minimum sfc is evidently a balance between nonisothermal losses and regenerator losses, both of which can become extremely large, but at opposite ends of compression ratio scale.

It seems clear that a reduction in loss impact would be beneficial in any further improvements in performance of the Stirling engines. However, if experience in other engines can be used as a guide, this is not likely to be very fruitful. Thus, higher temperatures is probably the more likely path. Given the large amount of internal power transfer required, and the reciprocating nature of the engine, it also seems clear that concepts to transfer heat with small sizes and weights, and materials to permit very high (mean) pressure operation would also pay high dividends.

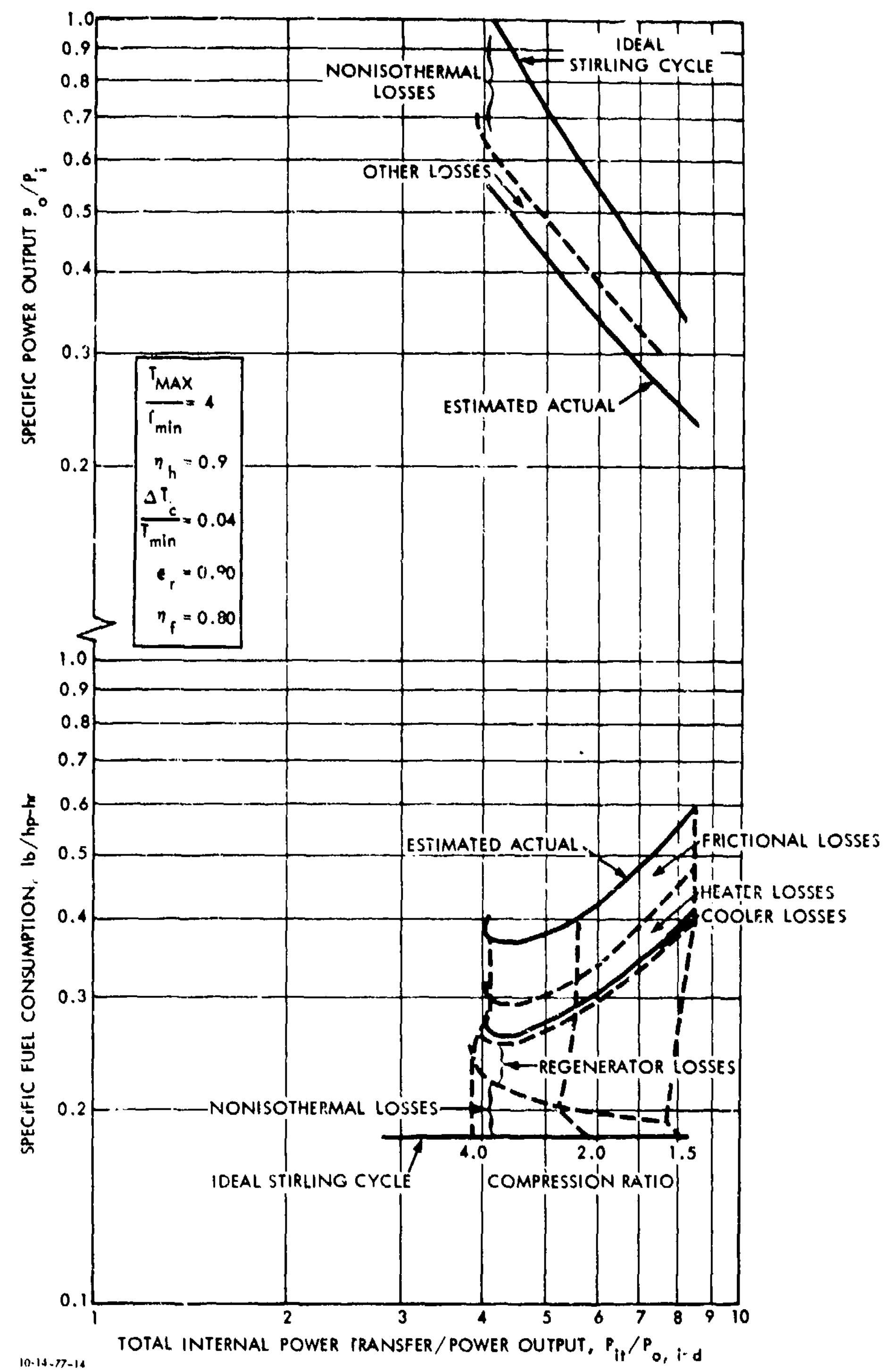

FIGURE IV-22. Impact of individual losses on approximate Stirling engine performance.

7. Concluding Remarks

As indicated at the beginning of this section, similarities among heat engines are emphasized by portraying their performance characteristics in terms of appropriate power transfer parameters. In the context of providing a framework for evaluating engine concepts, other than the ones considered here, it is perhaps useful to return to this overview. It will be recalled that in terms of ideal performance as a function of the ratio of internal power transfer to power output are, in order of desirability, Otto, Diesel, open Brayton, Stirling, and closed Brayton (see Fig. IV-2). The areas to be examined here are the impacts that actual performance and component loss-size-weight relationships have on the resulting sfc_e-sw_e-sv_e relationships.

a. Actual Performance. The estimated actual performance of all engines examined here is shown in Fi IV-23. With respect to the estimated current state of the art, the diesel engine clearly emerges as possessing the best characteristics, due primarily to advantages in part-power operation and compression ratio limitations in the Otto. The other engines remain in essentially the same relative order of desirable characteristics as indicated by their ideal performance. It seems clear, then, that ideal performance, expressed in the manner of Fig. IV-1 is a useful guide to the relative actual performance of heat engines. However, it is to be noted that the impact of losses on performance is large (for example, about 30 percentage points in thermal efficiency), and obviously requires evaluation in any heat engine.

In looking at the potential limits shown in Fig. IV-23, perhaps the most significant is the emergence of engines which are two types of internal power transfer components (the compound Diesel, the regenerated open Brayton, the Stirling, and the closed Brayton) as having relatively more desirable characteristics. Perhaps it is not too much of a generalization to attribute this

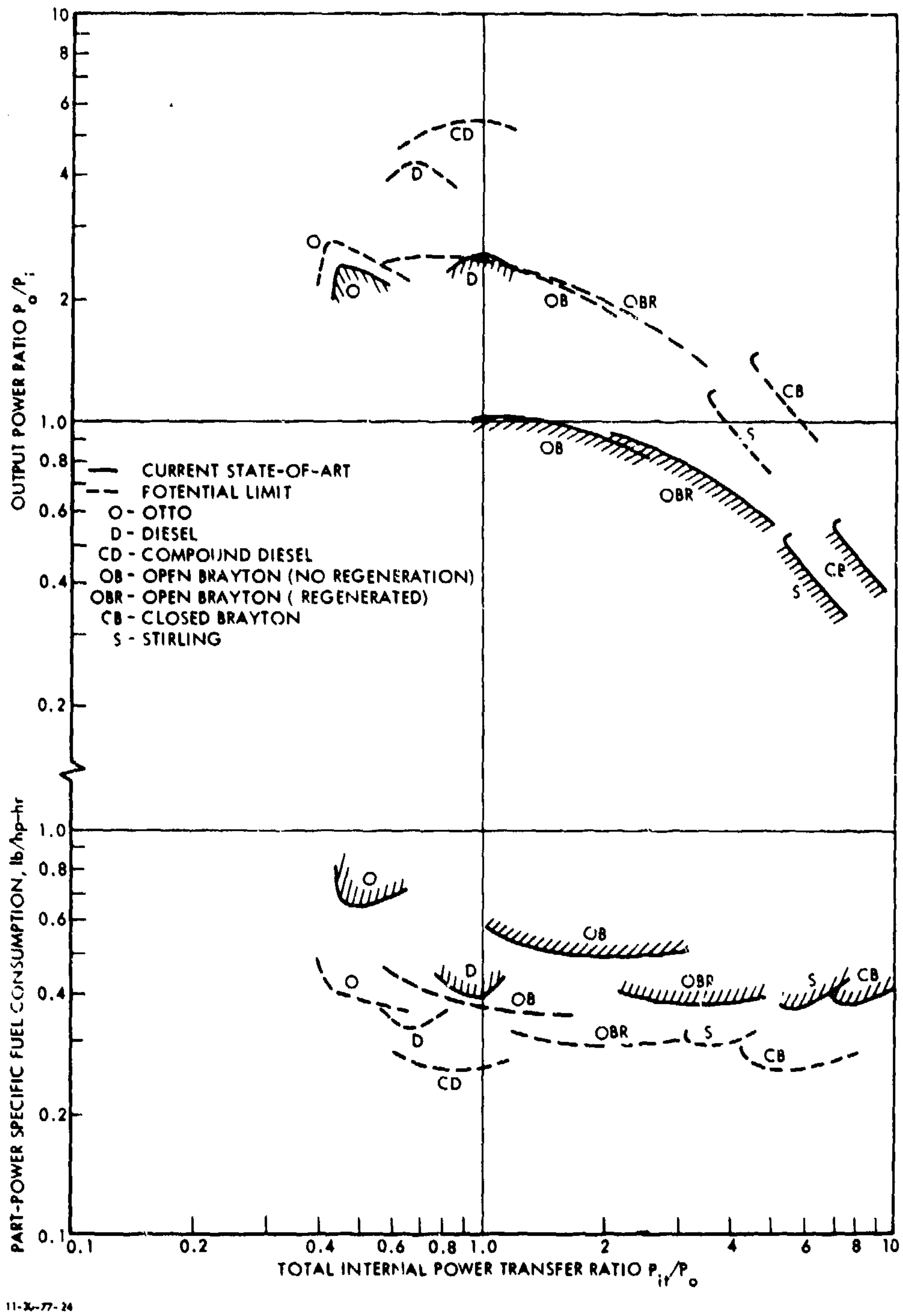

FIGURE IV-23. Estimated state-of-the-art and potential-limit performance of various types of heat engines.

feature to the fact that to obtain improved performance (sfc, particularly) it is essential to increase the level of internal power transfer, and to the speculation that no single power transfer component has characteristics suitable for dealing with the entire amount required.

As a final observation, there do not appear to be any large gaps possible in ideal performance characteristics in between those of the engines examined here. This is not to say, of course, that there are no new engine concepts which may offer improved characteristics; rather, that there are no obvious areas in which to concentrate efforts. In any event, it seems clearly desirable that any future engine concept offer some advantage in actual performance characteristics, in the terms of Fig. IV-23.

b. Component Weight-Performance Characteristics. The eventual sfc_e-sw_e-sv_e relationship for a heat engine is determined not only by its actual performance characteristics, as discussed above, but also by the size/weight-performance characteristics of the components employed to accomplish the necessary power transfers. In a crude way, the characteristics of the major components examined in this study are shown in Fig. IV-24. These are of course oversimplified (and in some cases highly tentative pending more actual data) in that the loss-weight relationship depends upon properties of the working fluid, thermodynamic conditions, and power levels. The following nominal conditions are representative of the relationships shown in Fig. IV-24: air as the working fluid with atmospheric pressure as a minimum; for axial compressors and turbines, 10,000 hp and a pressure ratio of 20; for centrifugal compressors, 100 hp and a pressure ratio of 5; for heat exchangers, 10,000 hp and an available temperature difference of 1000°F; and for reciprocating devices, 10 hp/cylinder. The examination of these components here indicates that they all have some rather basic loss levels that cannot be overcome; thus, improvements in characteristics for

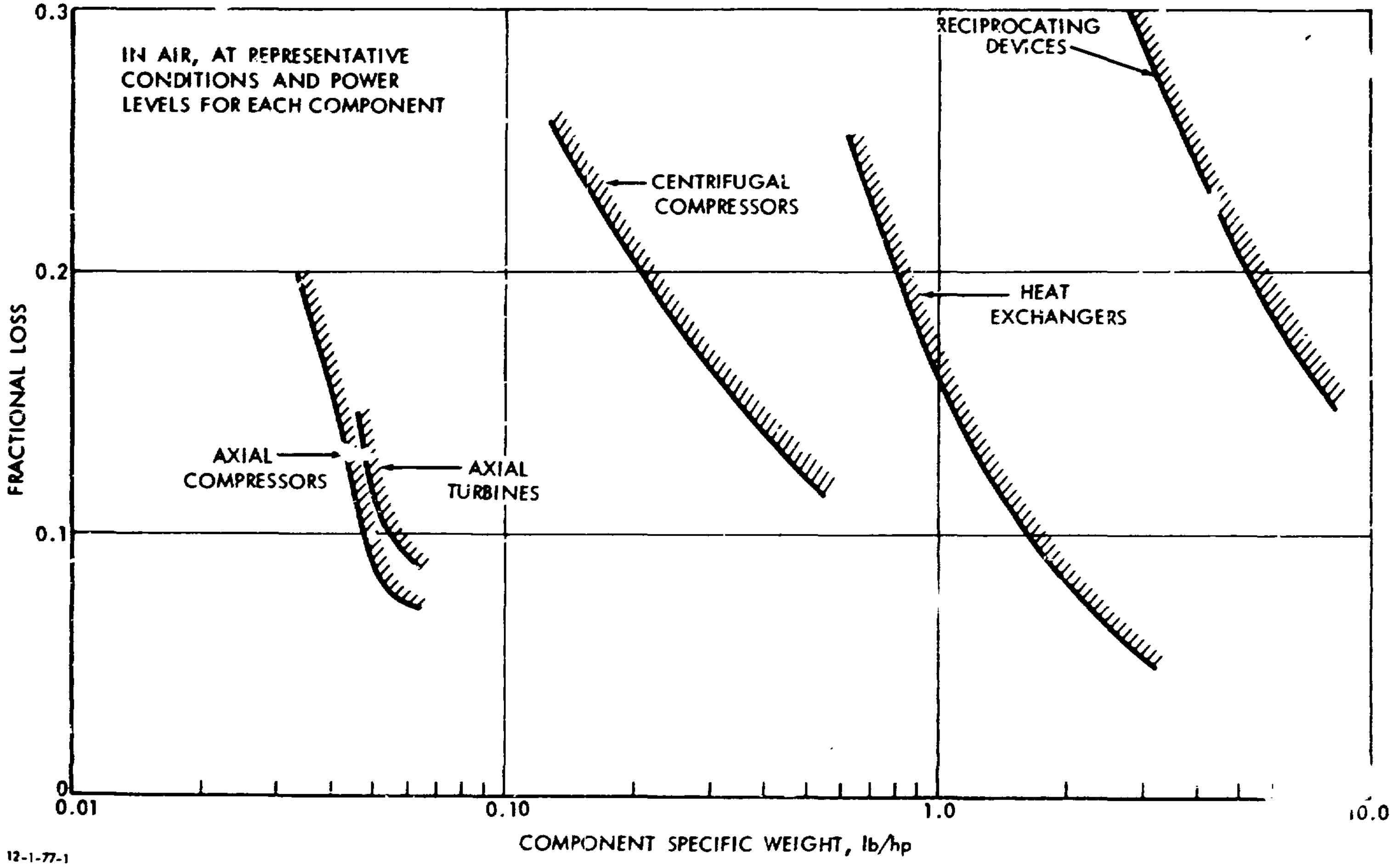

FIGURE IV-24. Loss-weight characteristics of some major components used in heat engines.

these components must arise from improved materials, on the one hand, or improved working fluids, thermodynamic conditions, and power levels, on the other.

It seems desirable that any new component concepts should compare favorably with existing ones in the terms of Fig. IV-24. The resultant impact on the engine sfc-sw$_e$ can be relatively evaluated by observing that, crudely, the impact on engine efficiency can be written as:

$$\Delta\eta = \left(\frac{P_{loss}}{P_{component}}\right)\left(\frac{P_{component}}{P_{add}}\right) ,$$

where $P_{loss}/P_{component}$ is the fractional loss of the component, and $P_{component}/P_{add}$ is the ratio of power transferred by the component to the heat addition rate of the engine. Similarly, the impact on specific weight is given by

$$\Delta\left(\frac{W}{P_o}\right) = \left(\frac{W}{P}\right)_{component} \left(\frac{P_{component}}{P_o}\right) .$$

The only additional information needed is of course the actual cycle performance, as described earlier.

c. <u>Engine sfc-sw-sv Relationships</u>. The actual performance and the component loss-weight characteristics combine to yield the engine sfc-sw characteristics, shown in Fig. IV-25 for the engines examined here. Again, it may be observed that the engines with the relatively more desirable actual performance characteristics in Fig. IV-23--those with two types of internal power transfer components--also maintain their advantage here.

The weight associated with the total power transfer, in a gross sense, is also of interest, and can be obtained from Figs. IV-23 and IV-25, with the following results at typical potential-limit points:

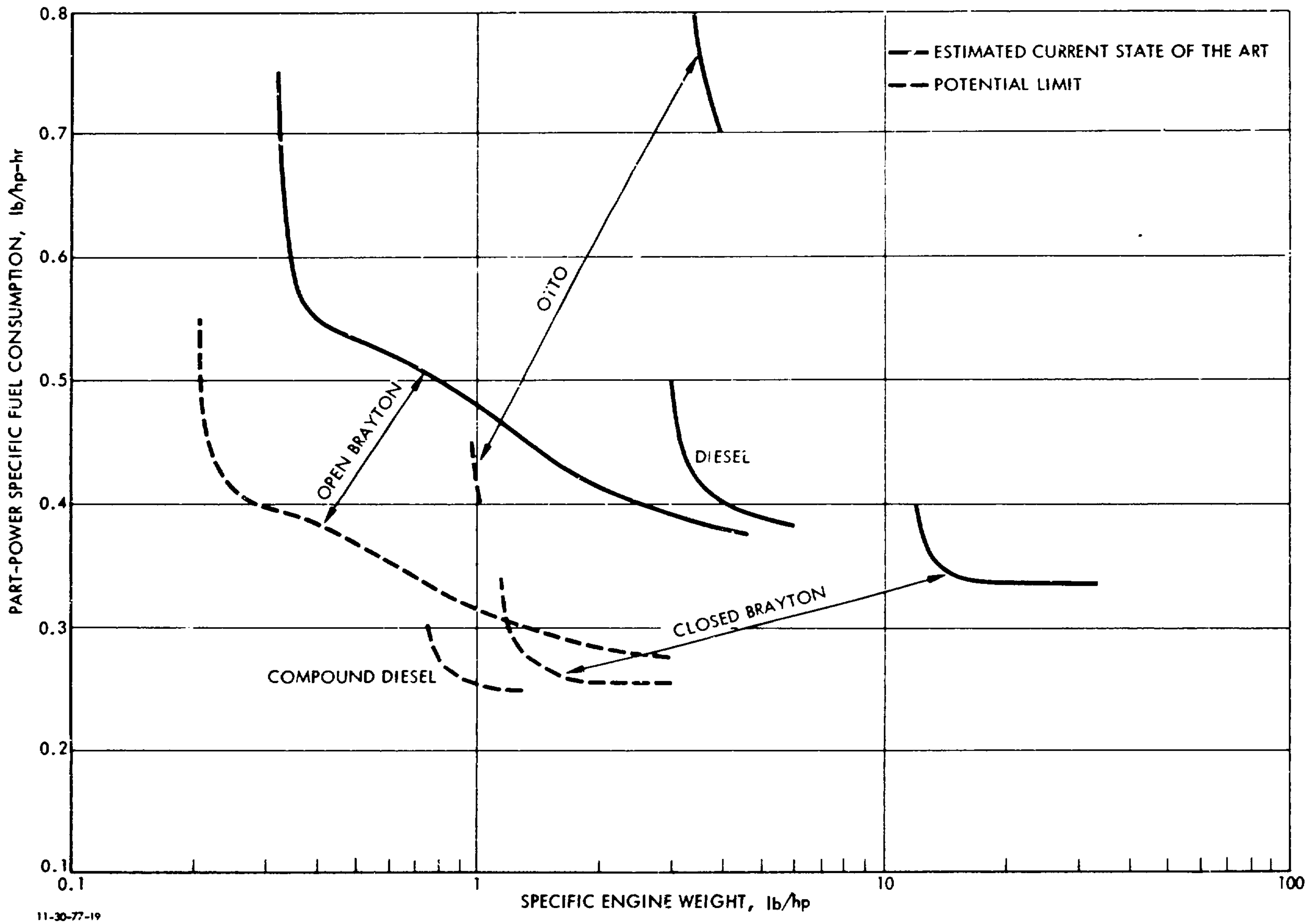

FIGURE IV-25. Estimated state-of-the-art and potential-limit performance of some types of heat engines.

Engine	Specific Weight (lb/hp)	Total Power Transfer / Output Power	Engine Weight / Total Power Transfer (lb/hp)
Compound Diesel	0.8	1.8	0.44
Open Brayton (Simple)	0.25	2.0	0.12
Open Brayton (Regenerated)	1.0	3.0	0.33
Closed Brayton	1.5	6	0.25
Otto	1.0	1.4	0.71
Stirling	?	5	?

It is apparent that the Otto fares the worst, due to the presence of reciprocating machinery and the inability to raise the density to alleviate it; as might be expected, the open Brayton fares the best, due to the superior weight characteristics of turbomachinery. The closed Brayton cycle evidently achieves some benefit from the use of helium as a working fluid. Although the Stirling engine was not evaluated nere, it seems apparent that, given reciprocating machinery, it will be very difficult to achieve a low weight per unit total power transfer, although use of hydrogen is obviously of benefit--but, for example, if it is assumed that a weight per unit power transfer of 1/2 that obtained in the Otto might be possible, then the limiting specific weight of the Stirling engine would be of the order of 1.5 lb/hp, which would be competitive with the other engines. Evidently, then, it is necessary to evaluate new engine concepts rather completely--ideal performance, actual performance, and component characteristics--if a reasonable assessment is to be made.

B. TRANSMISSIONS

1. General Considerations

As noted above for heat engines the objectives of this investigation are (1) to identify suitable goals and high-payoff areas of technology for some known types of transmissions, and

(2) to provide a framework for evaluating other transmission concepts. The characteristics of primary concern here are the efficiency η_x, the specific weight sw_x, and the specific volume sv_x.

a. **Functions**. The transmission as defined here involves all the machinery required to take the output shaft power of the engine and deliver input shaft power to the thruster. There are two basic functions involved: (1) torque conversion in order to match the engine output rpm to the thruster rpm requirements and (2) power transfer from the location of the engine to the location of the thruster.

The torque conversion function generally involves providing a number of reduction ratios to accommodate a range of power levels and thruster speeds. A typical example is in a tank, in which the transmission must deliver maximum power at high torque/low rpm for slope climbing, and also at much higher rpm for maximum level speed on a smooth surface. In addition a reversing function is required. Ships, on the other hand, may require only a single reduction ratio with speed control and reversing being provided by the engine input. The end application must therefore be considered in determining efficiency, specific weight and specific volume characteristics of torque conversion devices.

The power transfer function from engine location to thruster location may be simply a straight-line one-to-one transfer as in the propeller shaft on a ship, or it may require splitting the engine power between two thrusters and turning 90 degrees between engine output shaft and thruster input shaft as in a tank. Thus, again, the end application apparently is a significant consideration in assessing efficiency and size characteristics of power transfer devices.

To accommodate this dependence of the basic functions of transmissions on the application, a somewhat different

approach is required than used in the analysis of engines. In one sense the analysis is much simpler in that there are few basic variables involved, but on the other hand the application dependence makes it more difficult to develop general results. The basic approach taken in this study of analyzing the subsystem in terms of the energy conversion processes involved is still followed, however.

b. Technologies Considered. Three different types of transmissions have been evaluated in this study: (1) mechanical, consisting of gears and shafting; (2) hydrodynamic, consisting of a hydrodynamic torque converter plus mechanical gears and shafting; and (3) electrical, consisting of a generator, power conditioning controls, electrical cables and motors. The power conversion processes involved are:

1. Mechanical/mechanical conversion by gears.
2. Mechanical/hydrodynamic and the inverse, by the impeller and the turbine in a hydrodynamic torque converter.
3. Mechanical/electrical and the inverse, by electrical generators and motors.
4. Electrical/electrical by a power conditioning component.

The efficiency of the transmission subsystem depends on the number and types of the energy conversion processes involved. In mechanical/electrical and mechanical/hydrodynamic conversions there is an efficiency/size tradeoff possible, but in gears the efficiency is essentially independent of size. The overall size of a transmission subsystem is determined by the size of the power conversion components plus the other components needed to carry power between the conversion components.

In Appendices H and J the characteristics of mechanical, hydrodynamic, and electrical transmissions are examined. The following sections are based on these results and are presented in summary form.

2. Size and Efficiency Characteristics

a. Mechanical Transmissions. There are a number of empirical formulae for estimating gear weights. One in common use is the Dudlcy formula

$$W_g = C_1 \frac{Q^n}{K} ,$$

where W_g = weight of gears

K = the gear loading factor

Q = the torque factor

C_1 and n are empirical constants depending on the type of gears, and n is approximately unity for lightweight gears.

The torque factor Q is given by

$$Q = \frac{shp}{rpm} \frac{(R + 1)^3}{R} ,$$

where shp is shaft horsepower, rpm is shaft rpm and R is reduction ratio. Q is thus proportional to torque for a fixed reduction ratio; and from the equation for W_g, gear weight is proportional to torque and inversely proportional to the gear loading factor. This formulation is adequate for simple gear systems and was used to calculate gear weight for the waterjet thruster case discussed below.

The efficiency of mechanical transmissions can be considered independent of the weight. The rule of thumb for well-designed gears is a loss of 1% per gear mesh. This allows easy estimation of the efficiency of mechanical transmissions, which can be seen to be very high.

The weight of shafting, the other element of mechanical transmissions, depends on the torque and the length of the shaft

and can be easily calculated. As noted above, however, it is strongly dependent on the particular application being considered.

b. Hydrodynamic Transmissions. Hydrodynamic transmissions are defined here to mean a hydrodynamic torque converter together with mechanical gearing elements. In the land combat vehicles considered above, the hydrodynamic transmission includes a final drive which takes the output of the hydrodynamic unit, splits it and delivers it to the sprocket on each track. In addition, for the turbine engine there is a reduction gear ahead of the hydrodynamic unit to reduce the output rpm of the engine. The size and efficiency characteristics of these mechanical components can be analyzed as indicated above.

The hydrodynamic unit consists of a fluid torque converter together with gearing which can deliver power to the final drive through a range of rpm. The major losses in this unit occur in transferring energy into and out of the fluid, and these losses are quite size dependent. The efficiency/weight characteristics of a hydrodynamic transmission suitable for use in an LCV are estimated to be as shown in Fig. IV-26. The losses on this curve include a 4% loss for cooling and a 2% loss in the final drive. The improvement in efficiency at the potential-limit line comes largely from reduction of the fluid losses to estimated minimum levels (about two-thirds of current levels). A great deal of work has already been done to reduce these losses, and there is limited scope for further improvements. It was also estimated that a 25% reduction in total weight may be possible, mainly through improvement in material properties.

c. Electrical Transmissions. The size and efficiency characteristics of electrical transmissions are studied in Appendix J. The elements are taken to be electromechanical conversion devices, current switching apparatus, and distribution cabling. It is found that the size and efficiency is

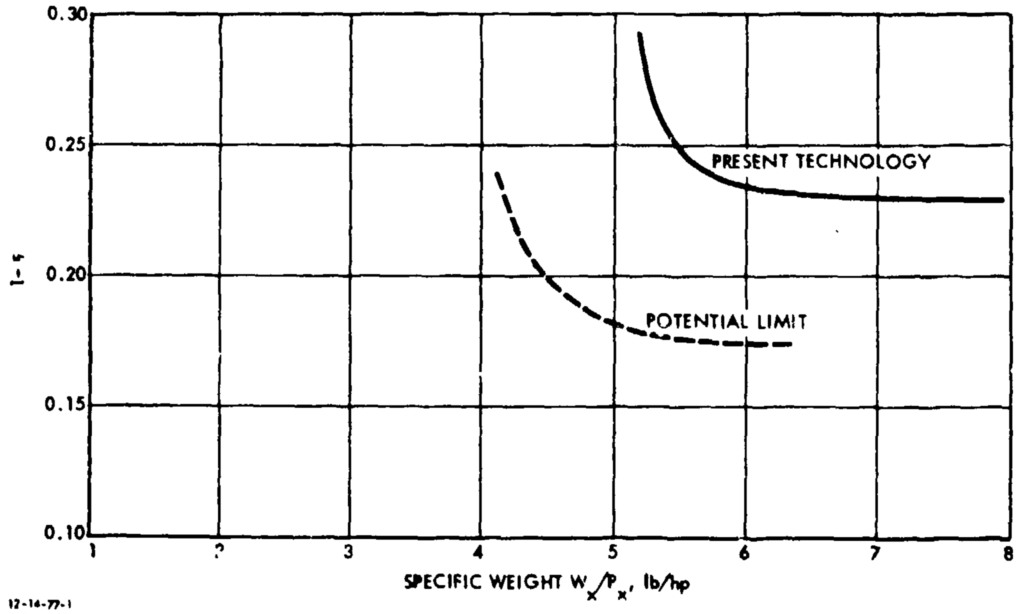

FIGURE IV-26. Efficiency and specific weight characteristics for an MBT hydrodynamic transmission (including final drive).

dominated by the electromechanical conversion devices. The size is also affected by the switching apparatus using present designs, but this could be relieved by design improvements, particularly in the cooling techniques.

The size of an electromechanical converter (i.e., a generator or a motor) depends on the power that can be generated per unit of volume. An empirical relationship that is commonly used for rough size estimates of commercial motors is

$$D^2L = a_2 \left(\frac{P}{n}\right)^{0.65} ,$$

where D = rotor diameter

L = rotor active length

P = power output

n = rpm

a_2 = a constant depending on the type of converter.

In Appendix J a similar expression is developed in which the exponent of (P/n) is 0.60 instead of 0.65, and a_2 is expressed in the physical parameters of the problem (Eq. J-61, p. J-57). In principle, this analytic expression could be used to examine the possible ways in which a_2 could be changed to improve power/volume relationships. This approach is being pursued in a later study.

Using conventional electrical machinery, an electrical transmission will be appreciably heavier than an equivalent mechanical or hydromechanical system for the military applications of interest. As a result there is considerable work under way to try to reduce the size of electromechanical converters. In Appendix J it is shown that one approach would be to reduce the efficiency of the converters and provide cooling. This is done in some aircraft equipment with remarkable size reductions.

Other approaches are the SEGMAG machines and superconducting machines. Rough estimates of size reductions by factors of three to six that may result from these approaches have been made in an internal MERADCOM report.* Such reductions could potentially make electrical transmissions competitive in the combat vehicles considered here.

3. High-Payoff Areas in Transmissions

The applications analyzed in Section III did not show payoff areas in hydrodynamic transmission systems as great as in engines. This is not because the transmissions are small but because the scope for improved weight and efficiency was judged to be smaller than in heat engines. Suitable goals for land combat vehicles (p. 92) are to reduce the weight of mechanical components by 30% and to reduce losses in the fluid mechanical elements by 25%.

C. THRUSTERS

1. For Land Combat Vehicles

a. General Considerations. The basic functions of thrusters for land combat vehicles are to support the vehicle and to provide sufficient ground contact area for developing thrust. In this study the thruster is taken to include the suspension, since this is part of the support function and intimately tied to the amount of unsprung weight in the rest of the thruster. Tracks and wheels were selected for the study done in Appendix K since they are the only types of thrusters in general use. Many special purpose thrust devices have been proposed and some have been developed particularly for use on very soft ground. None of these has come into general use, however, as competition to the wheel or the track.

*By A.L. Jokl and C.J. Heise, August 1976.

b. Size and Efficiency Characteristics. The analysis done in Appendix K shows that the weight of thrusters using tracks is proportional to the size of the vehicle, being about 20 to 22% of GVW. The reference designs used in Appendix A for both lightly armored combat vehicles and heavy tanks had thruster weights of 21.6% of GVW and this was used in all tracked vehicle calculations. The implication is that the weight of tracks is dictated by the support function.

In small offroad vehicles (up to a few tons in GVW) thrusters using wheels are about half the weight of tracks. As GVW is increased, however, the wheel size must increase to keep the ground pressure at acceptable levels for off-road use. It is shown in Appendix K that this causes the wheel size to grow more rapidly than the size of the vehicle, and as a result at GVWs above about 25 tons the track has a size advantage. It appears, therefore, that wheels may be competitive with tracks for lightly armored combat vehicles but not for MBTs. In addition, six- and eight-wheeled vehicles are needed and all wheels must be powered to provide adequate thrust. This complicates the transmission problem in the vehicle. On a total weight and size basis, and for armored combat vehicles, wheels appear to be competitive with tracks only up to a GVW of about 15 tons.

The efficiency of tracks is determined by the frictional losses involved in rotating the track and the slip losses between the track and the ground surface. From the analysis of traction done in Appendix K it was decided to take the frictional losses at 5% and to use 4% slip as representative of average load conditions for tracks. Wheels have the same slip losses but somewhat lower frictional losses.

c. Potential Improvements. The major payoff area here is in reducing the weight of tracked thrusters. Since volume does not also have to be reduced, this appears to be fertile ground for use of high strength/weight materials. It is possible that weight could be reduced also by some design innovations.

2. For High-Speed Ships

a. General Considerations. The choice of thrusters for high-speed ships is limited. The discussion in Appendix L shows that size considerations require that water, rather than air or air/water mixtures, be used as the thrusting medium. The basic options then are (1) to try to develop thrust in the high-velocity stream with a propeller, which leads to a supercavitating propeller design, or (2) to slow the stream down and pump it at low velocity, which leads to a waterjet design. These two approaches are analyzed in Appendix L and the results summarized here.

b. Size and Efficiency Characteristics. Size and efficiency cannot be treated independently in either of these thrusters. In general, they display the size/efficiency tradeoffs characteristic of power conversion devices. Size is also dependent on the propeller or pump rpm and as rpm is varied the reduction ratio from the engine output is changed, which changes the size of the transmission. It is convenient, therefore, to consider the transmission and thruster together. This is particularly true for the waterjet system since it is expected that the engine and pump will be close coupled, so the transmission is largely a reduction gear.

Such an analysis is done in Appendix L with the results shown in Fig. IV-27, where the specific weight is expressed in terms of shaft horsepower. The solid lines in this figure do not represent current capability but are an estimate of what may be eventually attained. These calculations were used in Section III to define the characteristics of the waterjet thruster for the HSS calculations.

The efficiency and specific weight of a supercavitating propeller were also calculated in Appendix L and are shown in Fig. IV-28. In this case the transmission was not included since it is dependent on the separation distance between engine

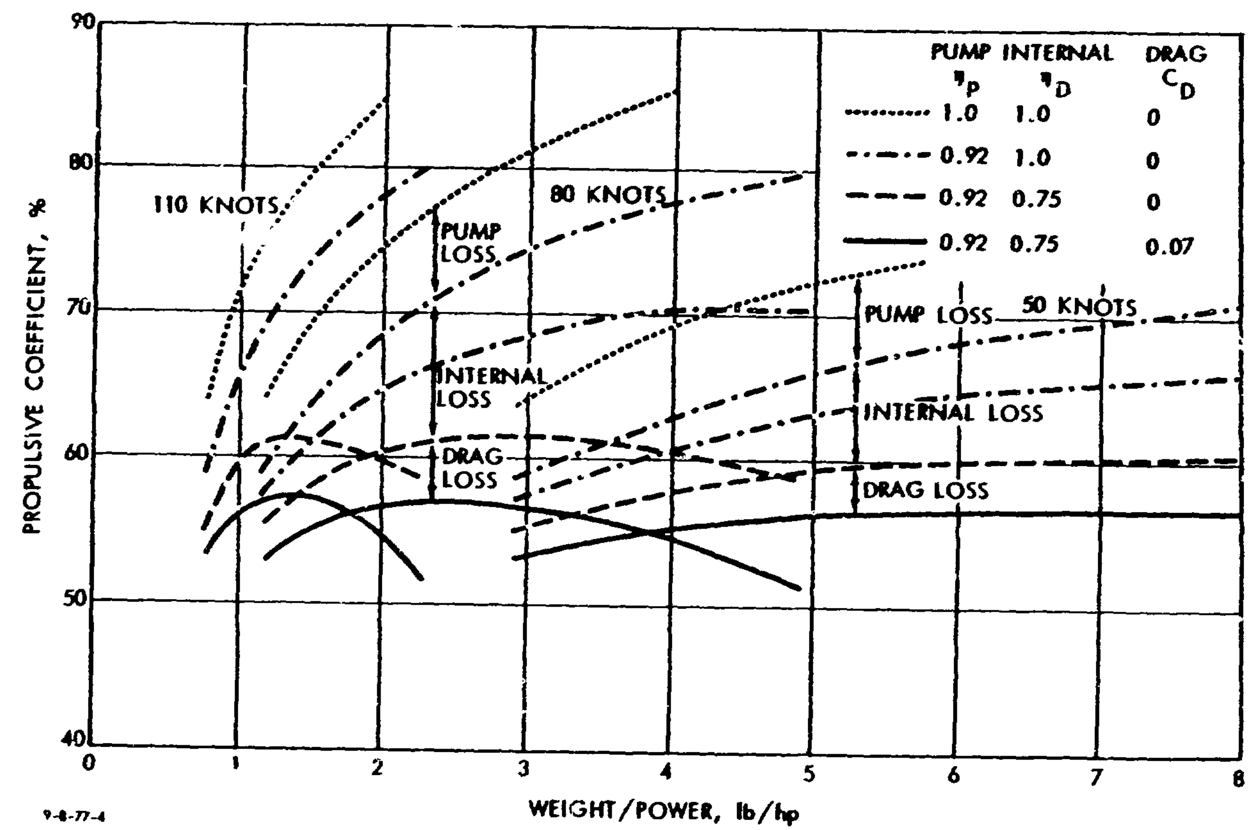

FIGURE IV-27. Efficiency and system specific weight for flush inlet waterjet systems (20,000 hp).

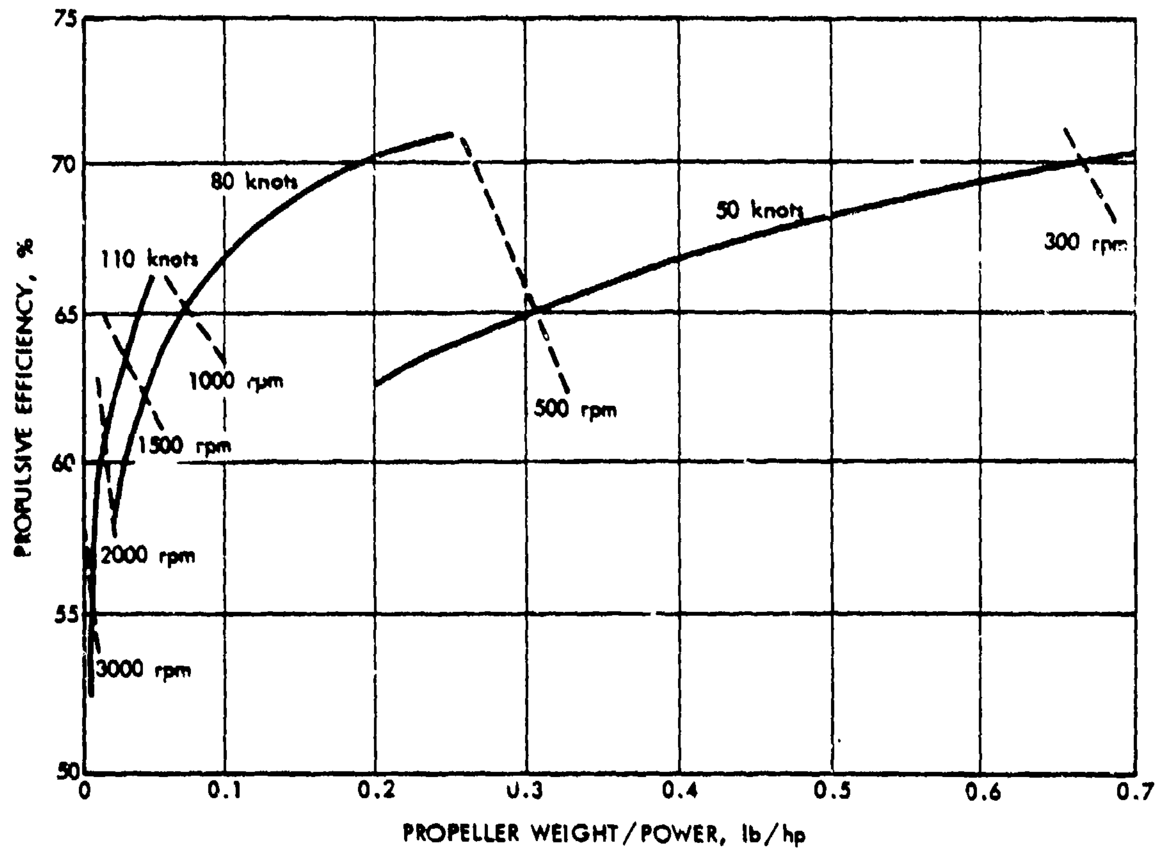

FIGURE IV-28. Propulsive efficiency, specific weight, and revolutions per minute of supercavitating propellers (20,000 hp).

and thruster in an actual design. One of the problems with using supercavitating propellers is that in current HSS designs it is difficult to locate the propeller and engine near together or even to line them up, and hence the transmission becomes a major component of the system. The evidence is that this transmission problem makes the supercavitating propeller system unattractive in current SES designs, and hence it was excluded from the HSS calculations.

c. High-Payoff Areas. The HSS calculations indicate that the greatest payoff for the waterjet thruster is in improving its efficiency. The estimated potential limit represents a reduction of about 40% in losses. Suitable goals may be to reduce the drag loss, internal loss, and pump loss by one-third. This is largely a design problem.

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Recent technology improvements, state of development, and performance characteristics of the 100-Watt and 500-Watt Thermoelectric Power Sources are presented.

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MILITARIZED THERMOELECTRIC POWER SOURCES

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ABSTRACT

Thermoelectric power sources are being developed to provide multifuel, silent, maintenance free tactical power generators for forward area applications.

Recent technology improvements, state of development, and performance characteristics of the 100-Watt and 500-Watt Thermoelectric Power Sources are presented.

INVESTIGATIONS CONDUCTED at the US Army Electronics Technology and Devices Laboratory (ERADCOM) on the use of thermoelectric energy conversion for power generation have shown the potential to fabricate power sources covering the range of output power from 50 milliwatts to 1500 watts. Models of lightweight, liquid hydrocarbon fueled thermoelectric power sources have been fabricated in 100 watt, 500 watt, and 1100 watt sizes. The 500-Watt and 100-Watt models are at a more advanced state of development and have been tested extensively. The 500-Watt Thermoelectric Power Source is intended to replace troublesome gasoline engine-driven generator sets which are noisy, unreliable, and require frequent maintenance. The 100-Watt Thermoelectric Power Source is planned to fill a need for small, lightweight, silent energy sources for tactical applications.

The 500-Watt Thermoelectric Power Source has completed feasibility tests to determine its performance reliability for military applications over a wide range of environmental conditions. These tests were conducted under field conditions by soldiers representative of those who will operate and maintain the equipment when it is issued to the Army for field use. The unit successfully powered a variety of communication and electronic equipments demonstrating the feasibility of using a thermoelectric generator as a source of power for military equipment. During these tests some deficiencies were uncovered, namely, improper operation with diesel fuel oil (DF-2), accumulation of carbon in critical parts of the burner system when operated at low temperature (-30°C), and formation of fuel vapor in the fuel line during operation at high ambient temperature (40°C) causing sputtering, flame out, and unstable combustion conditions. These deficiencies compromise the multifuel capability, the low maintenance goal, and the safe operation of the unit.

This paper presents the results of a study conducted to resolve these problems, and describes the means devised to correct deficiencies. A technique for increasing the overall efficiency of the thermoelectric power source, by preheating the primary air for combustion, is also described with test results included.

THERMOELECTRIC POWER SOURCES DESCRIPTION

The configuration of the 500-Watt Thermoelectric Power Source is shown in Figure 1.

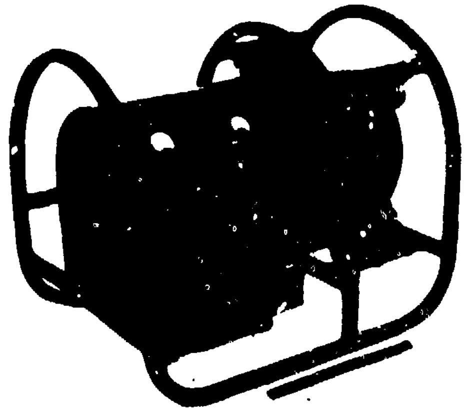


Fig. 1 - 500-Watt Thermoelectric Power Source

The cylindrically shaped thermoelectric converter, which constitutes the heaviest component of the unit, is horizontally mounted to lower the barycenter of the power source for mechanical stability. It is surrounded by the tubular shroud on the right side of the unit. The section on the left encases the cooling fan, fuel pump, and burner tube, which constitutes the initial part of the burner system, and the instrument and control panel. A moisture-proof drawer, on the bottom of the unit, contains the electronic components which are readily accessible for maintenance.

Figure 2 shows the 100-Watt Thermoelectric Power Source in its early development configuration.

Fig. 2 - 100-Watt Thermoelectric Power Source

The supporting structure of this unit is now being ruggedized to withstand rough handling normally associated with field use. Its final configuration will be similar, except for size, to that of the 500-Watt Thermoelectric Power Source. The 100-Watt Thermoelectric Power Source is being designed as a manportable unit to directly power communication-electronic equipment in forward areas and to sustain equipment operation during extended missions. A self-contained fuel tank which comprises the bottom section of the structure is designed to contain sufficient fuel for 8 hours continuous operation.

Table 1 shows the principal physical and performance characteristics of the two thermoelectric power sources.

Table 1 - Physical and Performance Characteristics of Thermoelectric Power Sources

	100 Watt Thermoelectric Power Source	500 Watt Thermoelectric Power Source
Multifuel Capability	Gasoline, Diesel, Kerosene, JP-4, JP-5	
Acoustic Noise	Inaudible beyond 30 m	Inaudible beyond 100 m
Efficiency	370 watthours/kg of fuel (2.8 percent)	400 watthours/kg of fuel (3.0 percent)
Operator Simplicity	Single switch activation (remote or local)	
Voltage Output	28 Vdc nominal (25-32 Vdc range) Regulation ± 1% (No-Load to Full-Load) Ripple (Peak to Peak) ± 1%	
MTBF	2000 hours	
Operational Temperature Range	-31.7°C (-25°F) to +51.7°C (+125°F)	
Operational Altitude Range	Sea Level to 1500 m	
Outside Dimensions	37 cm long, 20 cm wide 36 cm high	48 cm long, 63 cm wide 53 cm high
Weight	13 kg (30 pounds)	30 kg (66 pounds)

The same basic functions and subsystems characterize both units. The cross-sectional view of the 500-Watt Thermoelectric Power Source, presented in Figure 3, identifies and locates the major components.

Both units have the same thermoelectric converter configuration (Figure 4) with the combustion chamber constituting an integral part of the converter inside cylindrical structure. The outside shell of the converter features a spine-type cooling fin array. The converter is cooled on the outside by forcing ambient air across the heat dissipating fins. The annular region between the combustion chamber and the cold shell contains the thermopile. End bells are welded to both ends of the converter and provide a hermetically-sealed container for the lead-telluride (PbTe) couples. The container is backfilled with argon gas.

The PbTe couples are arranged in 32 rows parallel to the cylindrical axis of the combustion chamber. At the operating hot junction and cold junction temperatures of 565°C and 162°C, respectively, each couple develops a load voltage of 0.11 Vdc. Two hundred fifty six couples, connected in series electrically, produce a nominal 28 Vdc for the system of the 500-Watt Thermoelectric Power Source. (1)* The electrical gross power produced by the thermoelectric converter amounts to 640 watts.

*Numbers in parentheses designate References at end of paper.

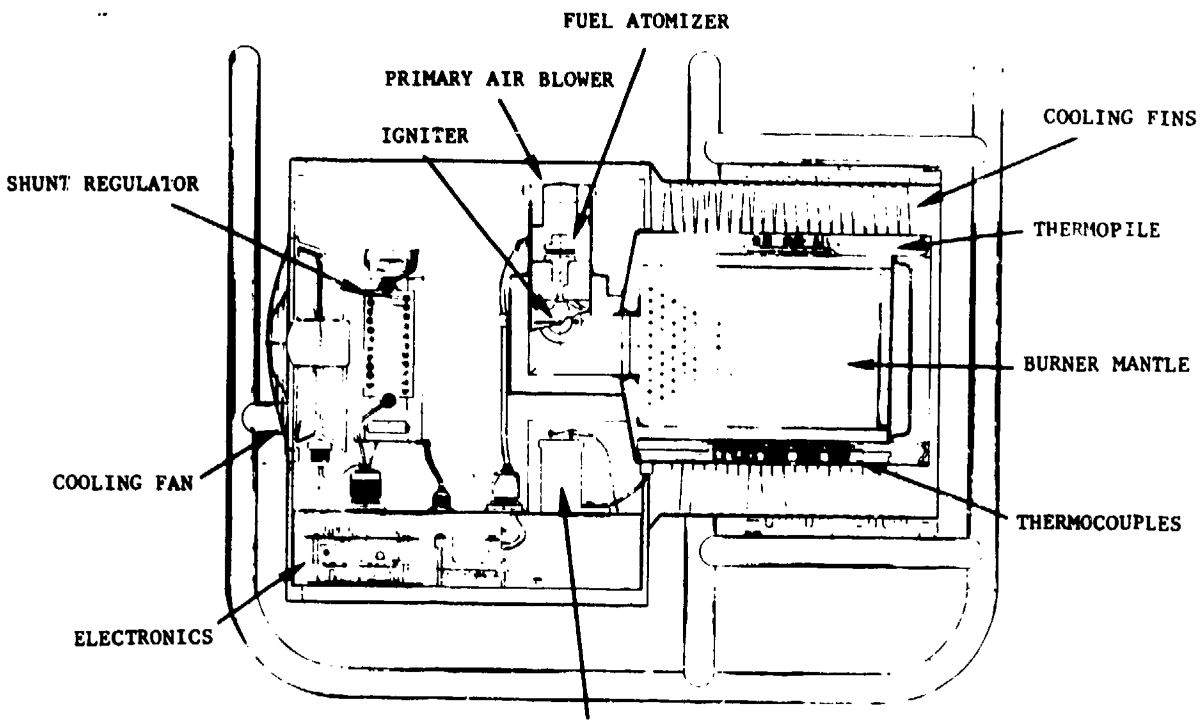
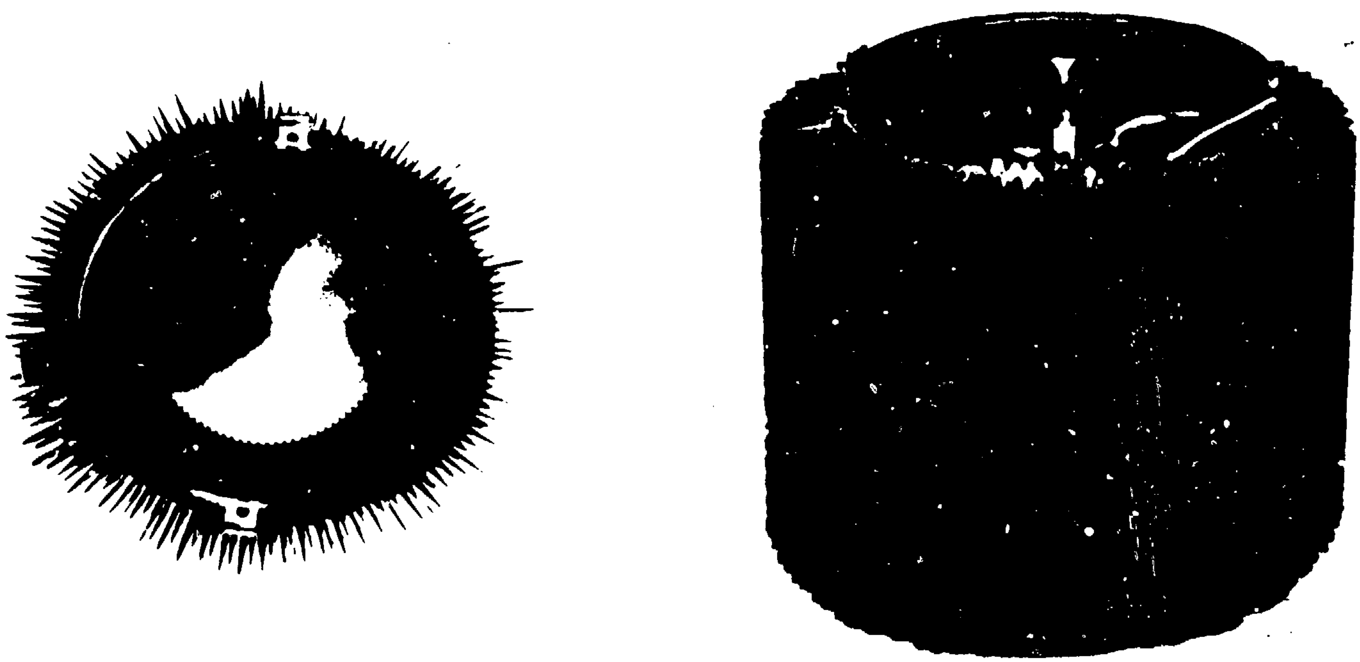


Fig. 3 - Cross-sectional View of the 500-Watt Thermoelectric Power Source



Top View

Side View

Fig. 4 - Thermoelectric Converter

A total of 120 couples, arranged in 24 rows and connected in series electrically, produce 12 Vdc for the system of the 100-Watt Thermoelectric Power Source. An electronic DC to DC converter is used to step up the voltage to the nominal 28 Vdc output.(2)

Raw power from the thermoelectric converter is conditioned by means of a shunt regulator which is part of the electronic subsystem. The electronic subsystem also protects the power source from overload and abnormal load conditions and automatically drives and controls the burner, fuel pump, and cooling fan to ensure that the thermoelectric elements operate at optimum efficiency.

The burner system provides heat to the thermoelectric converter through the combustion of liquid hydrocarbon fuels. Multifuel operational capability is achieved by using an ultrasonic atomizer. A transducer element, in the ultrasonic atomizer, vibrates at 75 kHz to produce a continuous mist of fuel. The atomizer, located inside the burner tube, is axially mounted in the middle of the primary air stream. Air for the combustion process is provided by the burner blower. Combustion, initiated by a spark gap igniter, commences near the tip of the atomizer and continues to completion inside the burner mantle. The function of the mantle is to distribute thermal energy uniformly to the thermoelectric converter in order to maintain uniform hot junction temperature at all of the couples.

DISCUSSION

The analysis of the deficiencies of the 500-Watt Thermoelectric Power Source indicated that the ultrasonic atomizer system was the component responsible for the poor performance of the unit when operated with diesel fuel oil (DF-2). The inability of this system to properly condition heavy liquid hydrocarbon fuels for combustion, restricted operation of the thermoelectric power source to lighter fuels such as jet fuels (JP-4 and JP-5) and gasoline. To correct this problem, a basic investigation was conducted on the atomization mechanism and on the characterization of the performance limits of the atomizer system utilized in this power source.

The use of ultrasonic atomization for the conditioning of liquid fuel is particularly appropriate for the thermoelectric power source application. With this technique, operational requirements of low and variable firing rate and minimal power consumption can be achieved simultaneously more effectively than with any other type of atomization technique. It is necessary that the fuel conditioning device operate readily with all types of liquid hydrocarbon fuels, withstand severe environmental stresses, and meet the requirements of unattended and reliable operation over long periods of time.

The process of liquid atomization using ultrasonic energy is accomplished by imparting sufficient kinetic energy to a liquid which covers a rapidly vibrating metallic surface. The kinetic forces generated by the vibrating surface cause the liquid to break up into minute droplets which are ejected from the surface.

Part of the experimental investigation on the atomizer was devoted to establish the character of the droplets comprising the spray. The fine mist produced by the rapidly vibrating tip is low in velocity since very little kinetic energy is imparted to the droplets by the atomization process. An experimental procedure for counting and measuring the diameter of the droplets was devised and utilized. (3) The smaller the average droplet size, the greater the total surface area exposed per unit volume of fuel atomized and greater the potential for efficient and complete combustion. The median droplet size of the mist produced is proportional to $f^{-2/3}$ (where f is the resonator frequency). It is advantageous to use as high a frequency as possible in order to obtain small droplets. By increasing the frequency, however, an amplitude of motion is reached in which the liquid disturbance is so violent that large drops are ejected rather than small droplets. This phenomenon, termed cavitation, is the result of the excessive energy ripping away large chunks of liquid from the main body of liquid. Therefore, proper ultrasonic atomization is limited to a definite region of tip motion bounded on the lower side by the threshold amplitude (the minimum amount of motion needed to produce atomization) and on the upper side by the cavitation. The corrected atomizer system, now implemented into the 500-Watt Thermoelectric Power Source, operates within these limits.

The motion of the vibrating surface is initiated by an electromechanical transducer (a lead zirconate titanate piezoelectric crystal) which converts electrical energy directly into mechanical energy. This transducer is an integral part of a resonator structure which is designed such that its dimensions coincide with an integer number of quarter-wavelengths of longitudinal sound waves at a selected vibrating frequency in the particular medium so that standing-waves can be supported. Experimental verification of the efficiency of an atomizer in converting electrical energy into motion of the atomizer tip was obtained by utilizing a diagnosis apparatus employing Michaelson interferometric techniques.

The atomizer study has provided a good understanding of the role played in the atomizing mechanism by the physical characteristics of the fuel and the complete performance characterization of the atomizer design. The results obtained have directed atomizer design corrections to account for the slightly higher values of viscosity, density, and surface tension which characterize the diesel fuels.

The atomizer body, incorporated in the 500-Watt Thermoelectric Power Source, is now fabricated from a high strength aluminum alloy, such as 7075-T6, or from titanium alloy Ti-6Al-4V. In the new resonator design the crystals are protected from fuel wetting which degrades the mechanical coupling. The oscillator used to provide the high frequency electrical energy to the atomizer was also redesigned to match the electrical and operating characteristics of the atomizer horn, and to minimize the AC input power level required.

Winter testing of the 500-Watt Thermoelectric Power Source equipped with the newly designed atomizer system has demonstrated that operation with DF-2 can be achieved at temperatures down to 0°C. This unit had already successfully performed with DF-1, JP-4, and gasoline, at temperatures down to -31°C. Although the experimental investigation was conducted on an atomizer system sized for the 500-Watt Thermoelectric Power Source, the results are quite general and are being implemented into the system of the 100-Watt Thermoelectric Power Source.

The voltage to the fuel pump is controlled by an electronic circuit which regulates the rate of fuel flow as a function of temperature, output voltage, and current of the thermoelectric converter.

The start-up sequence of the unit utilized in the feasibility tests is designed to provide, during the first few minutes of operation, a rate of fuel well in excess of the normal rate. This minimizes the time required for the system to reach operational readiness. With all fuels, except DF-2, the excess initial flow causes a moderate smoky condition. When starting with DF-2 a degenerative condition can occur. The initial smoke is observed to be very thick and contains a large amount of solid particulate. In several situations (during tests run in low temperature environment), this heavy smoke causes the partial clogging of some of the holes in the mantle creating higher impedance for the combustion gases and air starvation. This critical condition, together with a reduced evaporation rate of the excess fuel mixed with air at low temperature, causes heavy carbon buildup in critical parts of the burner with consequent system failure. A solution to this problem was achieved by an electronic control circuit which reduces the present fuel pump voltage and primary air at startup. The electronic control then gradually increases fuel rate and combustion air as a function of the increasing output voltage level of the thermopile. When the thermopile output voltage reaches a determined value (18 Volts), the normal fuel control takes over. Circuitry employing this basic control concept has been fabricated and successfully tested. The design of this control logic will be optimized to provide the best compromise for an automatic air/fuel ratio control for all the operational fuels. A study is in progress to utilize the same logic control to gradually increase the voltage to the cooling fan during the first few minutes of operation. Because the cooling fan is the auxiliary component requiring the highest power (75 watts), this will reduce the demand from the ancillary power source (usually a battery) used to start the unit.

During feasibility tests run in a high temperature environment (+50°C), and with the fuel container 15-20 feet away from the unit, the performance of the 500-Watt Thermoelectric Power Source was adversely affected by formation of fuel vapor in the fuel line. This vapor causes sputtering, unstable combustion, and occasional flameout. To correct this problem a vapor separator was devised which vents trapped air bubbles or fuel vapor present in the fuel line. The separator is comprised of a small chamber, inserted between the fuel pump and the atomizer, in which a float element actuates a vent valve mounted in the top wall of the chamber. During normal operation, the float keeps the valve opening sealed. Accumulation of vapor or air in the chamber causes a displacement of fuel from the upper section of the chamber. The resultant downward movement of the float opens the vent valve exhausting the vapor or air. This separator prevents spilling of fuel from the vent opening, thereby eliminating hazard conditions.

In addition to correction of the deficiencies evidenced by the feasibility tests, means of upgrading the basic subsystems of the 500-Watt Thermoelectric Power Source to improve overall efficiency were investigated. (4) Efficiency improvement is of major significance to the Army for better utilization of fossil fuel in essential combat missions and in support of energy conservation requirements. The combustion products, which leave the unit at 700°C, contain considerable heat at a relatively high temperature. A large percentage of this heat can be recovered through preheating the primary air for combustion. An air-to-air heat exchanger was devised and fabricated for this purpose. The heat exchanger, which is assembled at the exit of the combustion chamber, was designed for minimum size without introducing excessive impedance in the line of primary air for combustion. It has demonstrated the capability of preheating ambient air up to a temperature of 500°C. The output of the air-to-air heat exchanger is channeled to the burner through a duct on the outside of the unit. Since preheated air enters the combustion chamber at an elevated temperature (450°C to 500°C), a considerably lower fuel flow rate is needed to maintain the combustion chamber at the operational temperature required by the thermoelectric converter. Figure 5 shows a heat exchanger, assembled on a 500-Watt Thermoelectric Power Source, with related hardware to recycle the preheated air.

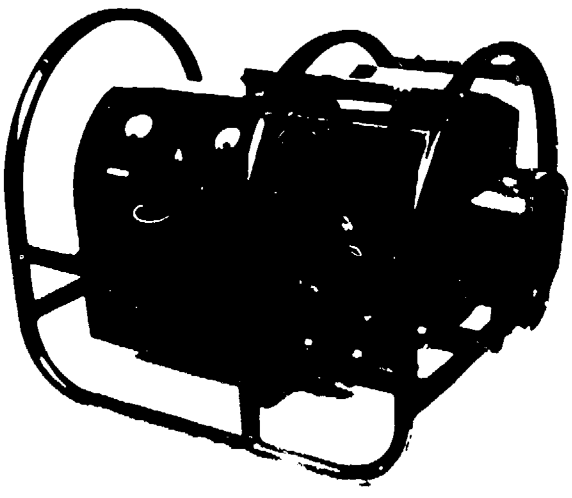


Fig. 5 - 500-Watt Thermoelectric Power Source With Heat Exchanger

This unit has been tested with JP-4, gasoline, and DF-2. Reduction of fuel consumption in the 25-27 percent range, obtained with all the unit's operational fuels, has been demonstrated (5) and is considered significant. The corresponding overall

efficiency has increased 33 to 37 percent. Additional gain in fuel saving is anticipated when heat losses, present in the configuration of this prototype heat exchanger, are eliminated. Tests indicate that other improvements in the operation of the 500-Watt Thermoelectric Power Source are obtained by utilizing the heat exchanger section at the exit of the combustion chamber. The exhaust gas temperature is lowered (from 700°C to 240°C), which significantly reduces the infrared signature detection of the unit, and combustion noise is muffled, which lowers the acoustic noise profile of this power source.

CONCLUSIONS

Development effort on critical subsystems of the 500-Watt Thermoelectric Power Source corrected operational deficiencies evidenced during the feasibility tests. The improved overall performance of this multifuel, silent, low maintenance power source improves its potential as a replacement for troublesome gasoline engine-driven generator sets which are noisy, unreliable, and require frequent maintenance.

The experimental study on the burner system of the thermoelectric power source has demonstrated the practicality of recovering a significant part of the heat exhausted with the combusted gases. Fuel reduction of 25 percent has been demonstrated with corresponding 33 percent increase in overall efficiency. In addition to these improvements in the burner system performance, the utilization of a heat exchanger at the exit of the combustion chamber considerably reduces the unit's infrared signature detection and muffles the combustion noise lowering the acoustic noise profile of this power source.

The 100-Watt Thermoelectric Power Source, now being reconfigured in a ruggedized supporting structure, will utilize the results obtained from the investigation of the 500-Watt Thermoelectric Power Source. The 100-Watt Thermoelectric Power Source technology is available for the development of small lightweight silent energy sources for tactical applications.

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